

MICROWAVE CHARACTERISTICS OF SiGe HBT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

VLSI Design & Embedded Systems

by

SANDEEP PONTATI

Roll No: 209EC2133



Department of Electronics & Communication Engineering

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Under the guidance of

Dr. Neti.V.L.Narasimha Murty



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National Institute of Technology

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Rourkela

CERTIFICATE

This is to certify that the thesis entitled, “**MICROWAVE CHARACTERISTICS OF SiGe HBT**” submitted by **SANDEEP PONTATI** (209EC2133) in partial fulfilment of the requirements for the award of Master of Technology degree in Electronics and Communication Engineering with specialization in “VLSI Design and Embedded Systems” at National Institute of Technology, Rourkela (Deemed University) and is an authentic work by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

Date:

Dr. Neti.V.L.Narasimha Murty

Dept. of E.C.E,

National Institute of Technology

Rourkela-769008

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Sandeep Pontati

ABSTRACT

In this thesis, I described about the basic introduction to SiGe Hetero-junction bipolar transistors, evaluation of SiGe HBT, SiGe HBT advantages over Si BJT's, the characteristics of Linearly Graded base doping and uniform base doping. Derived the S-parameters from the Complete Small Signal hybrid-pi Model of SiGe HBT. S-parameters of the Complete Small Signal hybrid-pi model of SiGe HBT calculated by using model equations of the Small Signal Model of intrinsic SiGe HBT within the frequency range of 0.2-50-GHz using parasitic effects. Intrinsic SiGe HBT model is having higher cutoff frequency than extrinsic SiGe HBT model because extrinsic SiGe HBT's having parasitic effects. The linearly graded-base SiGe HBT doping has smaller base transit time and larger cutoff frequency than the uniformly-base HBT doping.

S-parameters of the intrinsic small signal SiGe HBT and complete Small Signal of SiGe HBT are calculated by using various base widths. S-parameters of the Complete small signal hybrid-pi model of SiGe HBT are calculated by using different Ge concentrations. Further SiGe HBT are used to MMIC (Millimeter Microwave Integrated Circuit) Technology.

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CHAPTER-1

INTRODUCTION

1.1 Introduction:

Silicon is the material which has dominated the semiconductor industry for over 30 years. Bipolar junction transistors (BJTs) have the benefits of the silicon technology is very high integration and low-cost production, but are limited to lower frequencies.

Silicon has advantages than other Semiconductors

- Si is wonderfully abundant, and can be easily purified to low background impurity concentrations.
- Si can be grown in very large, virtually defect free single crystals yielding many IC's per wafer.
- Si has excellent thermal properties allowing for the efficient removal of dissipated heat.
- Si can be controllably doped with both n- and p-type impurities with extremely high dynamic range ($10^{14} - 10^{22} \text{ cm}^{-3}$).
- Si has excellent mechanical strength, facilitating ease of handling and fabrication.
- It is easy to make very low-resistance ohmic contacts to Si, thus minimizing device parasitic.

NEED FOR HBT:

The carrier mobility for both electrons and holes in Si is small, and the maximum velocity that these carriers can attain is limited to about 10, 00000 m/sec. low intrinsic speed in Si is problematic when operated in microwave frequency range

Heterojunction is the interface occurs between the two layers of dissimilar semiconductor materials. these semiconductor materials are unequal bandgaps compared to homojunction.

1.1.1 SiGe HBT:

The principal difference between the BJT and HBT is in the use of differing semiconductor materials for the emitter and base regions, forming a Heterojunction

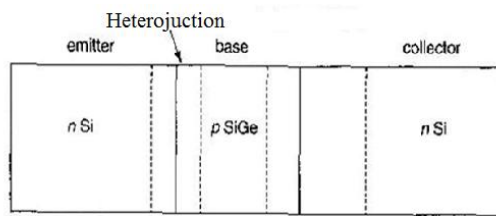


Figure 1.1 Block Diagram of SiGe HBT

The silicon-germanium heterojunction bipolar transistor is the first practical bandgap-engineered device to be realised in silicon. As a result of the bandgap engineering made possible by including a small amount of germanium in the base, one achieves

1. improved emitter injection efficiency;
2. reduced emitter charge storage;
3. reduced base transit time;
4. reduced output conductance;
5. improved current gain at low temperature.

Compared to III–V technologies, SiGe-technology offers the following advantages:

1. Low cost through compatibility with silicon CMOS;
2. uniformity and high yield across large wafers;
3. high thermal conductivity;
4. lower operating voltage.

The SiGe HBT offers several advantages over a Si BJT

1. A higher base doping concentration can be used to reduce base band gap and Decreasing the base resistance.
2. A reduction in the base transit time increases the f_T and f_{max} .
3. An increase in collector current density will allow high current gain with low base resistance.
4. Early voltage is higher at a given cut-off frequency.

1.1.2 History of SiGe Technology

The concept of combining silicon (Si) and germanium (Ge) into an alloy for use in transistor engineering is an old one, and was probably envisioned by Shockley in his early transistor game. However, because of difficulties in growing lattice-matched SiGe alloy on Si, this

concept is reduced to practical reality only in the last 15 years. SiGe HBT technology was originally developed at IBM for the high-end computing market that effort, however, failed to CMOS, primarily because of its high power consumption.

In the early 1990s, IBM refocused its SiGe program towards the rapidly developing communications market. Interestingly, for RF communications circuits, SiGe HBT consumes much less power than CMOS to achieve the same level of performance. Since then, significant progress has been made. SiGe technology is being developed and applied around the world, and is in the product roadmap of every major telecommunication company. Applications range from wired and wireless communications circuits, to disk storages, to high speed high bandwidth instrumentation. The use of discrete SiGe HBTs and amplifiers in wireless devices is common place. Integrated SiGe chips can be found in GSM and CDMA wireless handsets and base stations, wireless LAN chipsets, and high-speed 10-40 Gb/s synchronous optical network (SONET) transceivers.

1.1.3 Applications of SiGe HBT:

- SiGe HBT for Millimeter wave applications
- SiGe components can support high speed components for 10Gb/s Receiver and Transmitter IC's.
 - AGC amplifiers,
 - Integrated PLL based CDR,
 - low phase noise VCO
 - up to 3v laser/modulator driver

1.1.4 SiGe HBT vs GaAs HBT:

The SiGe HBTs are double heterojunction bipolar transistors (DHBTs) as the SiGe material is used as a narrow bandgap material in the p-type base. The emitter and the collector are silicon and have larger bandgap. The AlGaAs/GaAs and InGaP/GaAs HBTs benefit from a single heterojunction formed between the AlGaAs wide bandgap emitter and the GaAs p-type base. InP/InGaAs and InAlAs/InGaAs grown on InP Substrate give double heterojunction devices as both emitter and collector regions include wide bandgap materials.

1.2 Literature review:

Herbert Kroemer proposed on, A bipolar transistor with a wide-gap emitter. It improves the current gain and lower the injection deficit by using an emitter material with a wider band gap than the base material. The reason is an electron flowing from the base into the emitter is higher than the holes entering the base from the emitter. Since a decrease in the injection deficit by exponentially increasing of the base emitter voltage [1-2].

The idea of SiGe alloys to bandgap-engineer Si devices dates to the 1960's, the synthesis of defect-free SiGe films proved quite difficult, and device-quality SiGe films were not successfully produced until the early to mid-1980's. While Si and Ge can be combined to produce a chemically stable alloy (Si Ge or simply "SiGe"), their lattice constants differ by roughly 4% and, thus, SiGe alloys grown on Si substrates are compressively strained. (This is referred to as "pseudomorphic" growth of SiGe on Si, with the SiGe film adopting the underlying Si lattice constant.) These SiGe strained layers are subject to a fundamental stability criterion limiting their thickness for a given Ge concentration [3-4].

The fabrication of high performance transistors, and on the material and process challenges facing the implementation of SiGe HBT technology. The use of SiGe alloys for bandgap engineering of bipolar devices and the development of self-aligned, epitaxial base bipolar device structures will be discussed, including the most recent accomplishment of 75 GHz f_T heterojunction bipolar transistors, and the record sub-25 ps ECL ring oscillator delay. The design flexibility and trade-off's offered by SiGe heterojunction technology, like junction field/capacitance control, liquid nitrogen operation and complementary processes, are also reviewed, to assess the leverage of a SiGe base bipolar technology in high speed circuits [5-6].

J.S.Yuan proposed on the Modeling of Si/Si_{1-x}Ge_x HBT's. The model accounts for valence band and conduction band discontinuities, heavy doping effect and bias dependent emitter resistance and Heterojunction capacitances. The use of a smaller bandgap in the base of HBT increases minority carrier injection. This results in an increase of collector current and current gain. High base doping yields a smaller base resistance, lower noise

figure and reduced gate propagation delay. Because Si/SiGe HBT's have good potential in high frequency analog circuits and high- speed digital circuit applications [7].

SiGe-HBT structures were grown by an MBE-process. Essential for obtaining simultaneously high f_T and low R_{bi} ($0.7 \text{ k}\Omega/\square$ - $4 \text{ k}\Omega/\square$) was the high boron doping of the thin SiGe-base of $5 \cdot 10^{19}/\text{cm}^3$. Reduction of the thickness of the SiGe-layer from 40 nm to 25 nm resulted in the increase of f_T from 50 GHz to above 100 GHz. HBT doping profiles of both base and emitter are changed and the Ge content of the base is considerably higher (20 % - 30 % Ge) which requires low temperature. The advantage of this concept is based on the possibilities of high base dopings and low base sheet Resistivities for high frequency transistors [8].

The several large-signal HBT models are investigated to determine their usefulness at millimeter-wave frequencies. The most detailed model involves numerically solving moments of the Boltzmann Transport Equation. A description of the numerical model is given along with several simulated results. The numerical model is then used to evaluate two analytical HBT models, the conventional Gummel-Poon model and a modified Ebers-Moll model. It is found that the commonly used Gummel-Poon model exhibits poor agreement with numerical and experimental data at millimeter-wave frequencies due to neglect of transit-time delays. Improved agreement between measured and modeled data result by including transit-time effects in an Ebers-Moll model. This simple model has direct application to millimeter-wave power amplifier and oscillator design. Several measured results are presented to help verify the simple model [9].

J.D.Cressler proposed on SiGe Hetero-Junction Transistors. The silicon-germanium heterojunction bipolar transistor is the first practical bandgap-engineered device to be realised in silicon. The SiGe HBT promises faster switching speed than the silicon bipolar junction transistor (Si BJT), while maintaining the cost and yield advantages associated with silicon manufacturing [10-12].

Compared to III–V technologies, SiGe-technology offers the following advantages:

1. Low cost through compatibility with silicon CMOS;
- 2 uniformity and high yield across large wafers;
3. High thermal conductivity;

4. Lower operating voltage.

Due to its high-speed performance and mature silicon process, the SiGe HBT has emerged as technology of the choice for RFICs.

Sang K. Chun, Martin Tanner, Kang L. Wang are proposed on “Hole Mobility Measurements in Heavily Doped $\text{Si}_{1-x}\text{Ge}_x$ Strained Layers”. To optimize the design of $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ devices utilizing strained layers, accurate mobility data which includes dependencies on such variables as doping concentration, Ge content, temperature, and strain, must be obtained. Available mobility data for the strained layer case are limited by the critical thickness and by difficulties in accurately determining the free carrier concentration values. The Hall factor decreases with increasing Ge content, which may be due to additional scattering mechanisms introduced by Ge along with changes in the valence band structure as a result of strain [13].

Slavako Amon proposed the modeling of the collector current and base transit time in npn SiGe HBT. The evaluation of minority electron Concentration in the base and its dependence on doping concentration, temperature and Ge content is discussed in detail. It is shown that Ge-induced performance improvement of SiGe HBTs compared to Si BJTs is lowered at high doping concentrations in the base due to invalidity of Boltzmann statistics, which is more influential in SiGe due to lower hole effective mass [14].

C.W.Liu proposed on the base transit time of Si/SiGe heterojunction bipolar transistor is including the effects of minority carrier recombination lifetime and velocity saturation. The reduction of recombination lifetime in the neutral base region increases the base transit time as compared to the infinite recombination lifetime, and the finite saturation velocity also degrades the base transit time, as compared to the infinite saturation velocity. This analytical analysis can obtain the optimum design of Ge profiles in the base to minimize the base transit time. The extremely heavy doping of the base can degrade the base transit time significantly if the base width is larger than the diffusion length [15]

Sami Bousnina, Pierre Mandeville, Ammar B. Kouki, Robert Surridge, and Fadhel M. Ghannouchi are proposed on The direct extraction of heterojunction bipolar transistor (HBT) small-signal model parameters. For the development of microwave circuits using heterojunction bipolar transistors (HBTs), it is an accurate HBT equivalent-circuit model for

simulating circuit performances. The properties of this model should satisfy the following criteria: 1) the topology of the equivalent circuit model has to be selected by considering the device electrical response and 2) the model parameters-extraction procedure should be efficient and systematic. The extraction procedure allows for direct and fast calculation of a unique physically meaningful set of intrinsic parameters measured S-parameters for the whole frequency range of operation [16].

Lee proposed a model on An improved direct parameter extraction method of SiGe heterojunction bipolar transistors (HBTs) for the vertical bipolar intercompany (VBIC)-type hybrid- π model. All the equivalent circuit elements are extracted analytically from S -parameter data only and without any numerical optimization. Npn-type SiGe Heterojunction bipolar transistors (HBT's) have high cut-off frequencies, but low breakdown voltages due to their high current gain. We show that a SiGe layer in the emitter can increase the base current and hence the breakdown voltage while the collector current and cut-off frequency are not reduced The measurements of S -parameters are performed with a microwave probing system and a vector network analyzer over the frequency range 0.2–10.2 GHz[17]

Mukul K. Das, N. R. Das, and P. K. Basu are described the effects of Ge content and profile shape on the performance of a SiGe-based heterojunction bipolar transistor (HBT). The common-emitter current gain, the early voltage, and the transit time of SiGe HBTs are calculated and computed for different Ge profiles as well as the total Ge content in the base, considering uniform base-doping. Then the effects of the above on the cutoff frequency f_T and the maximum oscillation frequency f_{max} of the HBT are shown. It is seen that both the forward current gain and the transit time decrease with the change in profile from box to triangle, but the early voltage increases with a similar change. The increase of Ge content for the same profile results in a decrease of transit time. From the analysis, a large increase in f_T and f_{max} can be predicted with a suitable choice of Ge profile and the total Ge content in the base [18].

Rached Hajji and Fadhel M. Ghannouchi Small-Signal Distributed Model for GaAs HBT's and S-Parameter Prediction at Millimeter-Wave Frequencies A HBT distributed model can be used to simulate large size and high power HBT's operating at millimeter-wave frequencies where the propagating and coupling effects are significant. It has been

shown that accuracy in fitting a small-signal HBT model to the measured scattering parameters can be achieved by using a sliced model that includes the distributed effects. A bias dependent distributed model can be derived by modeling the active slice circuit at different bias conditions. Consequently, analytical expressions can be obtained for the bias-dependent intrinsic elements of the HBT. This constitutes an intermediary step in deriving a large-signal distributed model needed for analysis purposes of microwave/millimeter-wave nonlinear circuits such as mixers, frequency multipliers/dividers and amplifiers [19].

Shinichi Tanaka, Yasuchi Amamiya, Seiichi Murakami, Norio Goto, Yoichiro Takayama and Kajuhika Honjo are proposed Design Considerations for Millimeter-Wave Power HBT's Based on Gain Performance Analysis. Critical design issues involved in optimizing millimeter-wave power HBT's are described. Gain analysis of common-emitter (CE) and common-base (CB) HBT's is performed using analytical formulas derived based on a practical HBT model. While CB HBT's have superior maximum-gain at very high frequencies, their frequency limit is found to be determined by the carrier transit time delay. First, although CE and CB HBT's have the same f_{max} , CB HBT's have a superior gain in millimeter-wave bands because the 3-dB roll-off characteristics of the MSG extend to a much higher frequency range. Second, to fully exploit the potential gain of CB HBT's, care must be taken to keep the carrier transit time short, because otherwise the device suffers from a significant gain degradation when a high collector voltage is applied. Third, reducing the base resistance and collector capacitance is the key to improving the gain because they are the principal parameters that govern the MSG in a CB HBT [20].

H.J.Osten, D.Knoll, B. Heinemann, H. Rucker, and B. Tillack are proposed on Carbon Doped SiGe Heterojunction Bipolar Transistors for High Frequency Applications. The incorporation of low concentrations of carbon into the SiGe region of a heterojunction bipolar transistor (HBT) can significantly suppress boron out diffusion caused by subsequent processing steps. This effect can be described by coupled diffusion of carbon atoms and Si point defects. We discuss the increase in performance and process margins in SiGe heterojunction bipolar technology by adding carbon. SiGe-C HBTs demonstrate excellent static parameters, exceeding the performance of state-of the-art SiGe HBTs. The present interest in development of SiGe HBTs stems from their potential applications in integrated circuits operating at radio frequencies. Circuits operating in the range of several Gigahertzes

(GHz) are needed for wireless communication systems. Silicon bipolar transistors for high frequency operation require short base transit times, low base resistance, and low extrinsic parasitic. Heterojunction devices with a larger band gap in the emitter region and a smaller band gap in the base region enhance high frequency performance [21].

Guogong Wang, Jonghoo Park, Hui li, Zhenqiang Ma, Donald Lie, Jerry Lopez, and A. M. Hurtado are proposed on The influences of device size on the small- and large-signal performance of SiGe power HBTs. Due to the increased parasitic emitter and base resistances, both small- and large-signal power gain values of SiGe power HBTs degraded with the increase of device size. For small devices, parasitic are not dominant. The output power can be increased simply by increasing the device area. For large devices, due to the severe degradation of large-signal power gain output power ceases to increase with the increase of device area. Further increase of device area to increase output power should thus be avoided. [22].

Hai Huang, Zhenqiang Ma and Pingxi Ma and Marco Rananelli are proposed Influence of Substrate Parasitic Effects on Power Gain Relation between CE and CB SiGe HBTs The impact of substrate parasitic effects on the power gain relation between the CE and CB configuration of single emitter finger SiGe HBTs was studied. The intrinsic power gain relation between CE and CB configuration single finger SiGe HBTs is changed due to the influence of substrate parasitic effects. The substrate parasitics have little influence on power gain of CE configuration, but reduces the CB power gain dramatically, which makes the original power gain relation between CE and CB configuration lost. Substrate grounding can be used to effectively reduce the parasitic effects and to enhance the CB power gain[23].

Pradeep Kumar has proposed “Device parameter Optimization of Silicon Germanium HBT for THZ Applications” Ge grading on the performance of $\text{Si}_{1-x}\text{Ge}_x$ HBT is maximum oscillation-frequency f_{max} , cutoff frequency f_T , stability, Figure-of merit and various intrinsic as well as extrinsic parameters are calculated for different Ge concentrations with linear grading. The intrinsic and the extrinsic elements of model are obtained using a direct extraction method that the base resistance from the Z- parameters the base region optimization. Now-a-days research shows that applications in high-frequency communications and radar employ the wide bandwidth heterojunction bipolar transistors

(HBTs). ICs for 40 Gb/s transmission are currently in development in optical fiber communications [24].

Mukul Das, N.R das proposed “Performance Analysis of a SiGe/Si Heterojunction Bipolar Transistor for Different Ge-composition” the common-emitter forward current gain, Early voltage and total transit time of a SiGe heterojunction bipolar transistor (HBT) have been calculated and computed for different composition of Ge in the base. The results show that using suitable Ge-composition in the uniformly doped base, the transit time of the HBT can be significantly increased. The calculated cut-off frequency (f_T) of the HBT increases with the increase in the total Ge-content, and for the same Ge-content, it increases with the change in profile gradually from ‘box’ to ‘trapezoidal’, and then to ‘triangular’ type [25].

1.3 Scope of Thesis:

The scope of the thesis is organized as mentioned below

- a. Understand the material Properties of SiGe HBT
- b. Studied the characteristics of the Uniform-Base and Graded-base SiGe HBT
- c. S-parameters of the Complete Small Signal Model of SiGe HBT is calculated by using Model equations of Intrinsic Small Signal model of SiGe HBT with in the frequency range of 0.2- 50 GHz
- d. Compares the S-parameters of Complete Small Signal Model of SiGe HBT and Intrinsic Small Signal SiGe HBT Frequencies.
- e. Compares the S-parameters of the Complete model SiGe HBT and Intrinsic model HBT for Uniform Base doping and Graded-Base Doping.
- f. Calculated the Complete Small signal model of SiGe HBT of the different Ge concentrations.

CHAPTER-2

Material Properties & S-parameters of SiGe HBT

2.1 Material Properties of SiGe HBT:

Silicon and germanium are completely miscible over the full range of compositions and hence can be combined to form SiGe alloys with the germanium content ranging from 0 to 1 (0–100%). Their lattice constant differ by roughly 4.2%.

SiGe has a diamond-like lattice structure and the lattice constant is given by vegard's rule [26]

$$a_{SiGe} = a_{Si}(1-x) + a_{Ge}x \quad (2.1)$$

a_{Si} = Silicon lattice constant is 0.357 nm

a_{Ge} = Germanium lattice constant is 0.356 nm

x = Ge mole fraction

When a SiGe layer is grown on a silicon substrate, the lattice mismatch at the interface between the SiGe and the silicon has to be accommodated. This can either be done by compression of the SiGe layer so that it fits to the silicon lattice or by the creation of misfit dislocations at the interface fig2.1 [5].

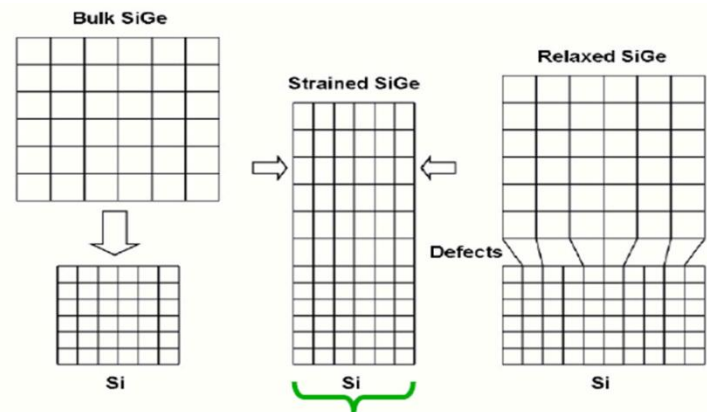


Figure 2. 1 Strain and relaxed SiGe on Si substrate

When SiGe layer grown on silicon by compression of the SiGe layer and it fits to silicon lattice is pseudomorphic SiGe layer is unstrained, or relaxed, and the lattice mismatch at the interface is accommodated by the formation of misfit dislocations. These misfit dislocations generally lie in the plane of the interface, as shown in above fig. but dislocations can also thread vertically through the SiGe layer.

2.1.1 Critical thickness:

An important concept in strained layer epitaxy is critical layer thickness. Critical layer Thickness arises because of a competition between strain energy and chemical energy.

The maximum thickness of SiGe that can be grown before relaxation of the strain occurs through the formation of misfit dislocations. This is known as the critical thickness of the SiGe layer, and depends strongly on the germanium content, as shown in below fig[10].

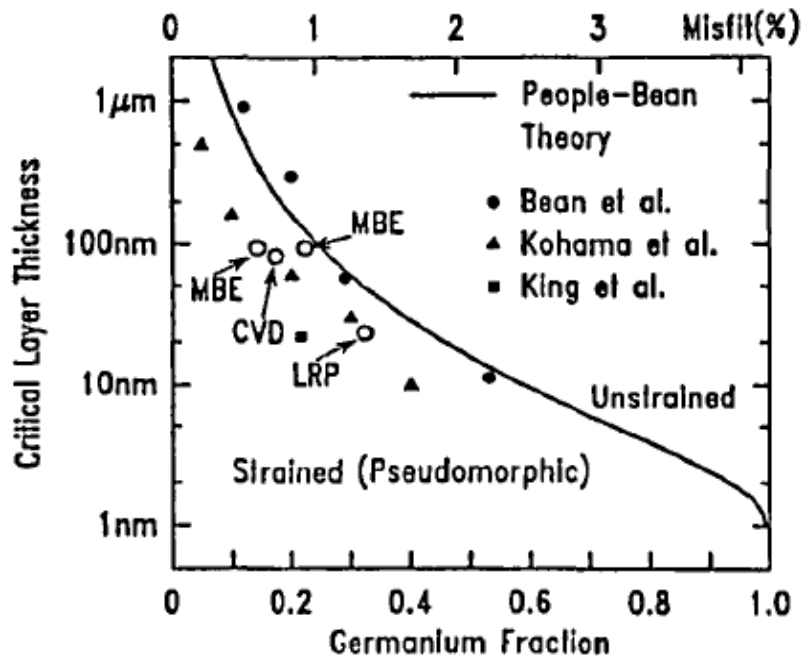


Figure 2.2 Critical thickness vs Ge fraction

Below the critical thickness, the minimum energy state of the bilayer system is achieved by strain.

Above the critical thickness, the minimum energy state is achieved by the formation of misfit dislocations.

The critical thickness is dependent up on the amount of lattice mismatch and material parameters as well as the properties of the dislocations that form in the particular material.

2.1.2 Band Structure of SiGe:

SiGe alloys have a smaller bandgap than silicon partly because of the larger lattice constant and partly because of the strain. The below figure Shows that the variation of bandgap with germanium percentage for strained and unstrained SiGe [26].

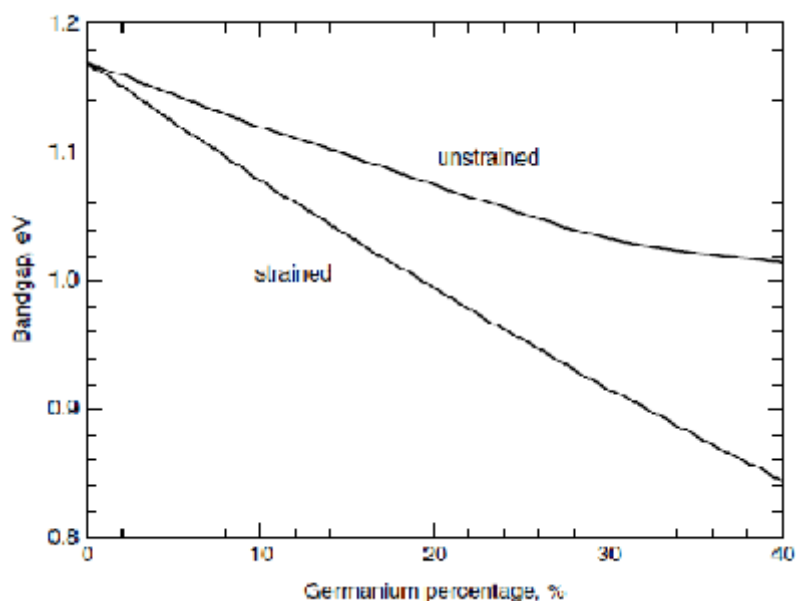


Figure 2. 3 Bandgap as a function of Ge percentage for Strained and unstrained SiGe

The variation of bandgap with germanium content for strained SiGe can be described by the Following empirical equation [26]:

$$\dots\dots\dots (2.2)$$

2.1.3 Dielectric Constant:

The dielectric constant of $\text{Si}_{1-x}\text{Ge}_x$ can be obtained by linear interpolation between the known values for silicon and germanium using the following equation [26]

$$\epsilon(x) = 11.9(1+0.35x) \dots\dots\dots (2.3)$$

When abrupt heterojunctions are used, conduction band spikes can form at the interfaces.

At the base-emitter junction, such a spike can reduce the bandgap improvement, introduce a potential source of non-uniformity, and provide a sink for space charge recombination. At the edge of the base-collector junction, a conduction band spike can act as a barrier to minority-carrier transport across the base, resulting in increased charge storage and neutral base recombination.

2.1.4 DC characteristics:

The dc consequences of introducing Ge into the base region of an SiGe HBT can best be understood by considering an energy-band diagram of the resultant device and comparing it to Si. The barrier height to electron flow from emitter to base (conduction band barrier) is much smaller in the SiGe HBT than the Si BJT. This means that the collector current at a given base-emitter voltage will be bigger in a SiGe HBT than in a Si BJT. The barrier height to hole flow from the base to the emitter (valence band barrier) is approximately the same in the SiGe HBT and the Si BJT, which means that the base currents of the two types of device will be approximately the same [27].

The Collector Current of SiGe HBT is

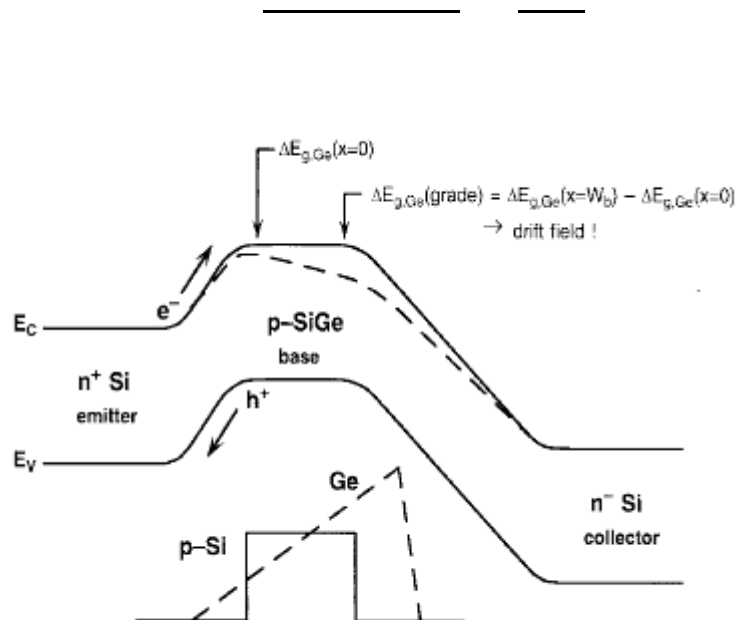


Figure 2. 4 Energy band diagram for a Si BJT and graded-base SiGe HBT

Ge is compositionally graded from the emitter-base (EB) junction with lower concentration to the collector–base (CB) junction with higher concentration and it is shown as dashed line in Figure (1). Due to this impact, the SiGe HBT consists of a finite band offset at the EB junction and a larger band offset at the CB junction. Bandgap grading is easily used for position dependence of the band offset with respect to Si. An electric field is produced by such position dependence in the Ge induced band offset in the neutral base region. This effect aids the transportation of minority carriers (electrons) from emitter to collector, which in turn improve the frequency response [12].

The Ge-induced reduction in base bandgap takes place at the EB edge of the quasi-neutral base $\Delta E_{g,Ge}(x=0)$ along with the CB edge of the quasi-neutral base $\Delta E_{g,Ge}(x=W_b)$. Thus the graded bandgap is given by equation as

$$\dots\dots\dots(2.4)$$

A linearly graded germanium profile file Across the base, the equation for the collector current of a Graded-base SiGe HBT is [26]

$$\dots\dots\dots(2.5)$$

D_{nb} = the diffusion coefficient of the minority- carrier electrons in the base = —

= intrinsic carrier concentration of SiGe

$$\dots\dots\dots(2.6)$$

an “effective density-of-states ratio” between SiGe and Si according to [27]

$$\gamma = \dots\dots\dots(2.7)$$

x = Ge mole fraction

an effective doping concentration in the base

$$= \dots\dots\dots(2.8)$$

Apparent band gap narrowing in the base described by the following empirical equation [28]

$$= 18.7 \text{ ———}$$

The Base Current of SiGe HBT is [26].

$$\text{—————} \text{ ———} \text{(2.9)}$$

the diffusion coefficient of the minority- carrier holes in the emitter

$$= \text{ ———}$$

an effective doping concentration in the emitter

$$= \text{—————} \text{(2.10)}$$

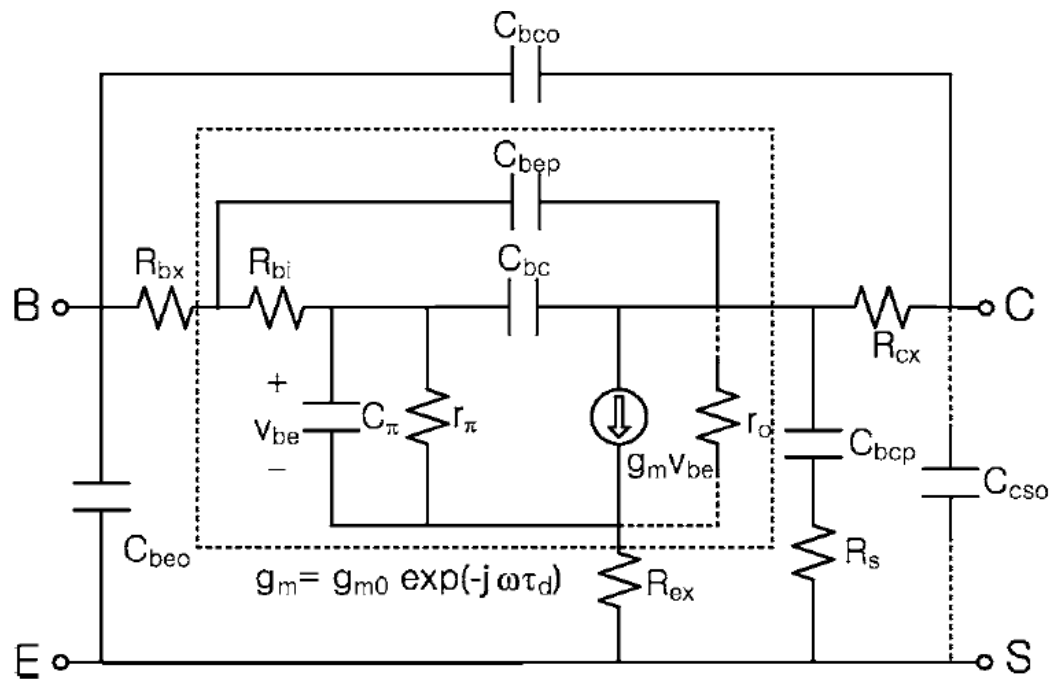
Apparent band gap narrowing in the emitter described by the following empirical
Equation [29]

$$= 18.7 \text{ ———}$$

2.2 Small Signal model of SiGe HBT:

The small signal model of SiGe HBT is based on Hybrid- π equivalent circuit of the VBIC-compact model. The hybrid-pi model is a popular circuit model used for analyzing the small signal behavior of bipolar junction and field effect transistors. The model can be quite accurate for low-frequency circuits and can easily be adapted for higher frequency circuits with the addition of appropriate inter-electrode capacitances and other parasitic elements

The small signal model of SiGe HBT circuit is divided into two parts. First one is Intrinsic HBT and second one is the Extrinsic HBT.

Figure 2. 5 Small Signal model of SiGe HBT hybrid- π model

The Intrinsic HBT is the inner part containing the bias- dependent intrinsic elements. The intrinsic elements are intrinsic base resistance (R_{bi}), base-emitter capacitance (C_{π}), base-emitter resistance (r_{π}), base-collector resistance (C_{bc}) and transconductance (g_m). Extrinsic HBT is the outer part is bias- independent of extrinsic element. The extrinsic elements are extrinsic resistance (R_{bx}), collector resistance (R_{cx}), emitter resistance, parasitic capacitances (C_{bcp} , C_{beo} , C_{cso}) and substrate resistance [15].

2.2.1 Base resistance:

Base resistance is one of the most important electrical parameters of the bipolar transistors. It limits the input capacitance can be charged and therefore bipolar transistors do not operate at high frequencies predicted by the forward transit time. Base Resistance gradually decreasing with increasing Base bias current.

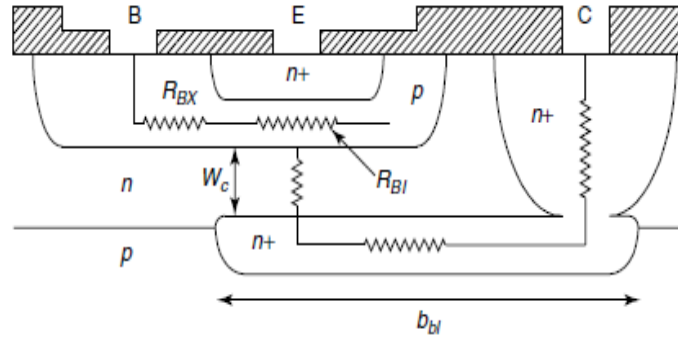


Figure 2. 6 The cross section view of components of base and collector resistance

The Base resistance can be divided into two parts,

- 1) Intrinsic base resistance
- 2) Extrinsic base resistance.

The Total Base resistance is adding of these two resistances.

2.3 Intrinsic Small Signal of SiGe HBT:

2.3.1 Introduction:

The Intrinsic HBT is containing the bias-dependent intrinsic elements. The intrinsic elements are intrinsic base resistance (R_{bi}), base-emitter capacitance (C_{π}), base-emitter resistance (r_{π}), base-collector resistance (C_{bc}) and transconductance (g_m).

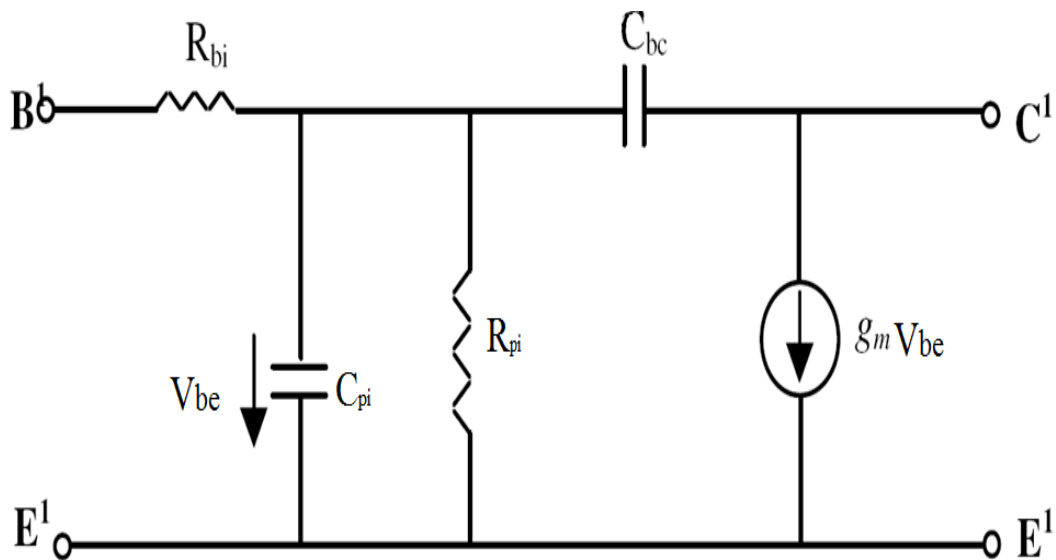


Figure 2.7 Intrinsic small signal model of SiGe HBT

2.3.2 Intrinsic base resistance:

The intrinsic base resistance is the resistance of the active base region, which is the region located under the emitter as shown in fig2.6. It depends on the transistor geometry and intrinsic base sheet resistance. The intrinsic base resistance (R_{bi}) is the current dependent part of the total base resistance due to conductivity modulation of the internal base sheet resistance. The reduced base-width modulation (The Early effect) in SiGe HBTs of the output conductance can be neglected.

$$= C \frac{W_e}{l_e} \dots\dots\dots(2.13)$$

is constant,

W_e =Emitter width,

l_e = length of the emitter,

R_{SBI} =intrinsic base sheet resistance

n_B^2 is two base contacts,

If the transistor has only one base contact, the base current enters from only one side of the emitter and hence the path length for the current flow is the complete emitter width. If the transistor has two base contacts, the current enters from the both sides of the emitter, so the path length for the current flow is halved. A halving of the base resistance arises because two base contacts are in parallel. So the base resistance is reduced if two base contacts are used [26].

2.3.3 Collector-Base Capacitance (C_{μ}) :

Collector-Base capacitance includes a depletion capacitance. Junction capacitance is related to the Space charge that exists in the depletion layer of pn junction.

a) GRADED JUNCTION:

In a Linearly Graded junction, the net doping on both sides of the junction, and consequently the ionized charge densities in the depletion region vary linearly.

The electrostatic parameters of a linear graded junction depicted in below figures.

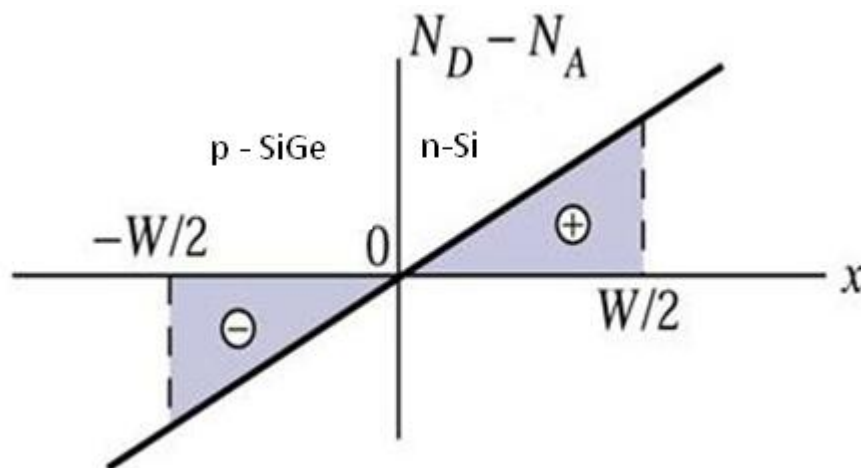


Figure 2. 8 Graded junction Space charge distribution

For an impurity concentration gradient () in the depletion region.

The Poisson eq for the graded junction is

$$\frac{dE}{dx} = -\frac{q}{\epsilon_0 \epsilon_r} N_A x \quad 0 < x < -x_p \quad \dots\dots\dots(2.14)$$

Electric Field is

$$E = -\frac{q}{2\epsilon_0 \epsilon_r} N_A x^2 \quad 0 < x < -x_p \quad \dots\dots\dots(2.15)$$

ϵ_r = dielectric constant of Si = 11.9

– Dielectric constant of SiGe (from eq 2.3)

W- Depletion region width

Case 1:

For $x > -x_p$

$$\frac{dE}{dx} = 0$$

$$E = 0$$

Take integration on both sides

$$E = -\frac{q}{2\epsilon_0 \epsilon_r} N_A x^2$$

$$E = -\frac{q}{2\epsilon_0 \epsilon_r} N_A x^2$$

$$\dots\dots\dots(2.16)$$

case 2:

$$0 < x < -x_p$$

$$\frac{dE}{dx} = -\frac{q}{\epsilon_0 \epsilon_r} N_A x$$

$$= -\frac{qN_A}{\epsilon_s} x$$

$$E_n(x) = -\frac{qN_A}{\epsilon_s} x - \frac{qN_D}{\epsilon_s} x \dots\dots\dots(2.17)$$

$$= -\frac{qN_A}{\epsilon_s} x + \frac{qN_D}{\epsilon_s} x \dots\dots\dots(2.18)$$

The built-in potential (V_{bi}) is

$$= -\frac{qN_A}{\epsilon_s} x - \frac{qN_D}{\epsilon_s} x \dots\dots\dots(2.19)$$

$$= -\frac{qN_A}{\epsilon_s} x$$

Substituting eq 2.18 in above eq

$$= -\frac{qN_A}{\epsilon_s} x - \frac{qN_D}{\epsilon_s} x \dots\dots\dots(2.20)$$

Substituting eq. 3.6 and 3.7 in eq.3.10

$$= -\frac{qN_A}{\epsilon_s} x - \frac{qN_D}{\epsilon_s} x$$

$$= -\frac{qN_A}{\epsilon_s} x - \frac{qN_D}{\epsilon_s} x$$

$$= -\frac{qN_A}{\epsilon_s} x - \frac{qN_D}{\epsilon_s} x$$

$$\begin{aligned}
 &= \frac{q N_A}{2 \epsilon_s \epsilon_0} \left(\frac{W}{2} \right)^2 \\
 &= \frac{q N_A W^2}{4 \epsilon_s \epsilon_0} \\
 &= \frac{q N_A W^2}{4 \epsilon_s \epsilon_0} + \frac{q N_D W^2}{4 \epsilon_s \epsilon_0} \dots\dots\dots(2.21)
 \end{aligned}$$

$$\begin{aligned}
 &= \frac{q N_A W^2}{4 \epsilon_s \epsilon_0} - \frac{q N_D W^2}{4 \epsilon_s \epsilon_0} \\
 &= \frac{q W^2}{4 \epsilon_s \epsilon_0} (N_A - N_D) \dots\dots\dots(2.22)
 \end{aligned}$$

From above equation depletion layer width W is

$$\begin{aligned}
 &= \frac{4 \epsilon_s \epsilon_0 (V_{bi} - V)}{q (N_A - N_D)} \\
 W &= \sqrt{\frac{4 \epsilon_s \epsilon_0 (V_{bi} - V)}{q (N_A - N_D)}} \dots\dots\dots(2.23)
 \end{aligned}$$

The depletion layer capacitance is given by

$$C_{BC} = \frac{q A W}{V_{bi} - V} \dots\dots\dots(2.24)$$

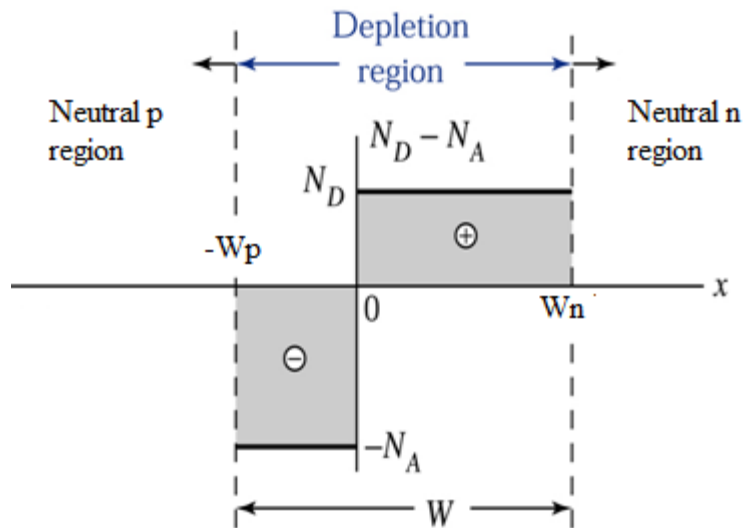
Substituting eq2.23 in above equation

$$\begin{aligned}
 C_{BC} &= \frac{q A}{V_{bi} - V} \sqrt{\frac{4 \epsilon_s \epsilon_0 (V_{bi} - V)}{q (N_A - N_D)}} \\
 C_{BC} &= A \sqrt{\frac{4 \epsilon_s \epsilon_0 q}{(N_A - N_D)}} \sqrt{\frac{V_{bi} - V}{V_{bi} - V}}
 \end{aligned}$$

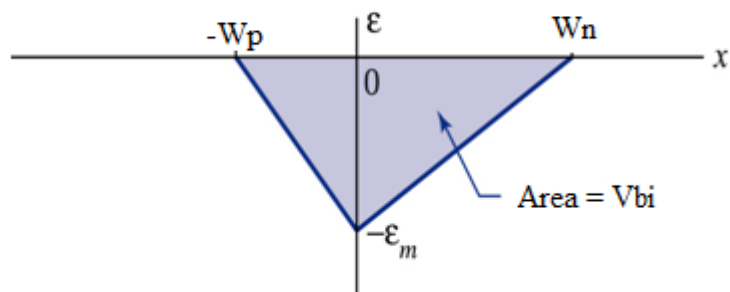
The depletion layer Capacitance C is function of applied bias V is given by

$$C_{BC} = A \sqrt{\frac{4 \epsilon_s \epsilon_0 q}{(N_A - N_D)}} \sqrt{V_{bi} - V} \dots\dots\dots(2.25)$$

b) Abrupt junction:



a) Space Charge Distribution



b) Electric field profile

Figure 2.9 Abrupt junction a) Space charge distribution b) electric field profile

Poisson's eqn for the abrupt junction is

$$\frac{d\epsilon}{dx} = \frac{\rho}{\epsilon_0} \quad \text{for } -W_p < x < W_n \quad \dots\dots\dots(2.26)$$

Electric field is

$$E = -\frac{qN_A}{\epsilon_0}x \quad \text{.....(2.27)}$$

For

$$E = -\frac{qN_A}{\epsilon_0}x$$

Take integration on both sides

$$\begin{aligned} \int E dx &= -\frac{qN_A}{\epsilon_0} \int x dx \\ E &= -\frac{qN_A}{\epsilon_0} x \end{aligned} \quad \text{.....(2.28)}$$

For $0 < x < W_n$

$$E = -\frac{qN_A}{\epsilon_0}x$$

Take integration on both sides

$$\begin{aligned} \int E dx &= -\frac{qN_A}{\epsilon_0} \int x dx \\ E &= -\frac{qN_A}{\epsilon_0} x \end{aligned} \quad \text{.....(2.29)}$$

The built-in electric field is maximum at the junction and goes to zero at the edges of the depletion region on both sides According to

$$\frac{1}{\epsilon_0} \left(\frac{q}{4\pi r^2} \right) = \frac{q}{4\pi \epsilon_0 r^2} \dots\dots\dots(2.30)$$

$$= - \frac{q}{4\pi \epsilon_0 r^2} x$$

Substituting eqs 2.28 and 2.29 in above eq

$$= - \frac{q}{4\pi \epsilon_0 r^2} x$$

$$= - \frac{q}{4\pi \epsilon_0 r^2} x - \frac{q}{4\pi \epsilon_0 r^2} x$$

Substituting eq. 3.6 and 3.7 in eq.3.10

$$= - \frac{q}{4\pi \epsilon_0 r^2} x - \frac{q}{4\pi \epsilon_0 r^2} x (x + \dots)$$

$$= - \frac{q}{4\pi \epsilon_0 r^2} x - \frac{q}{4\pi \epsilon_0 r^2} x$$

$$= - \frac{q}{4\pi \epsilon_0 r^2} x - \frac{q}{4\pi \epsilon_0 r^2} x$$

$$= - \frac{q}{4\pi \epsilon_0 r^2} x - \frac{q}{4\pi \epsilon_0 r^2} x \dots\dots\dots(2.31)$$

Charge conservation is expressed by the condition is

$$\dots\dots\dots(2.32)$$

From above eqn

$$\dots\dots\dots \text{ and}$$

$$\dots\dots\dots$$

Substitute above eqns in V_{bi} eqn

$$V_{bi} = \dots\dots\dots$$

$$= \dots\dots\dots$$

$$= \frac{q N_A W}{2} \left(\frac{W}{L_D} \right)^2 \quad \dots\dots\dots(2.33)$$

Similarly

$$\dots\dots\dots(2.34)$$

Depletion region width W is

$$W = \sqrt{\frac{2 \epsilon_s \epsilon_0 V_{bi}}{q N_A}} \quad \dots\dots\dots(2.35)$$

The depletion capacitance C is

$$C = \frac{Q}{V}$$

$$C = \frac{q N_A W}{V_{bi}}$$

$$C = \frac{2 \epsilon_s \epsilon_0 N_A}{V_{bi}} \sqrt{\frac{2 \epsilon_s \epsilon_0 V_{bi}}{q N_A}} \quad \dots\dots\dots(2.36)$$

2.3.4 Emitter-Base Capacitance (C_π):

The Emitter-base capacitance depends on both depletion and diffusion capacitances. Diffusion Capacitance is the minority carriers charge storage capacitance.

$$\dots\dots\dots(2.37)$$

C_{be} = Emitter-Base Depletion Capacitance

= forward transit Time

Transconductance

a) Forward Transit Time:

The forward transit time is the excess charge stored in the transistor when its emitter/base junction is forward biased and its collector/base junction zero biased. The forward Transit time is the sum of the Delay times in the various regions of the transistor

.....(2.38)

Base transit time (Base delay)

Emitter delay

= Emitter-Base depletion region delay

Collector-Base depletion region delay

b) Base Transit time:

The base transit time is defined as the ratio of the charge stored in the base to the collector Current.

—(2.39)

The charge stored in the base is [26]

— —

Substitute eqn in above eqn

— — —

Substitute I_c eqn in above eqn

.....(2.40)

Base width

Diffusivity of electrons in base

Base transit time is proportional to square of the base width.

The base transit time of graded base SiGe HBT is

$$\tau_B = \frac{Q_B}{I_C} \quad \text{.....(2.41)}$$

The base transit time (τ_B) is reduced by the drift field created by the bandgap grading. This grading is not required over the entire base region, since only the heavily doped region contributes to τ_B , bandgap variation across the base can improve significantly the base transit time. The bandgap reduction expected and measured for various Ge fractions in silicon [26].

The base transit time in a heterojunction bipolar transistor (HBT) can be shortened by providing a quasi-field across the base, i.e., grading the bandgap (Ge concentration) across the base [10]

c) Emitter Delay:

The emitter delay τ is defined as the ratio of the charge in the emitter to the collector current.

$$\tau = \frac{Q_E}{I_C} \quad \text{.....(2.42)}$$

The charge in the emitter is [26]

$$Q_E = \int_0^W n(x) q dx$$

Substitute eqn in above eqn

$$Q_E = \int_0^W n(x) q dx$$

Substitute I_C eqn in above eqn

$$\tau = \frac{q N_D W}{I_C} \quad \text{.....(2.43)}$$

The emitter delay of Graded-base SiGe HBT is

$$\tau = \frac{q N_D W}{I_C} \quad \text{.....(2.44)}$$

The decrease in β (due to the increase in current gain β) depends exponentially on the bandgap reduction at the edge of the base-emitter junction, and is inversely proportional to the variation in bandgap across the base [30].

d. Collector-base Depletion region Delay:

The collector/base depletion layer delay t_{cb} is determined by the time required for electrons to traverse the base/collector depletion region.

$$t_{cb} = \frac{W_{CBD}}{V_{sat}} \tag{2.45}$$

W_{CBD} = Collector-base depletion region width

V_{sat} = saturation velocity

Collector-base depletion region delay is reduced by decreasing the width of the Collector-base depletion region. It can be achieved by increasing the doping concentration in the collector.

2.3.5 Transconductance (g_m):

Transconductance is the differentiate collector current(I_c) with base emitter voltage (V_{be}).

$$g_m = \frac{dI_c}{dV_{be}} \tag{2.46}$$

I_c = collector current(from eqn 2.5),

V_{th} = thermal voltage

The transconductance g_m contains a delay component τ in order to model the excess phase shift which becomes noticeable at frequencies approaching f_T . At low bias currents, the excess phase delay decreases slowly with the increase in collector current, but once base-widening effects becomes noticeable it increases due to the increase in the forward transit time.

2.3.6 Base-Emitter Resistance:

The base –emitter resistance of Small Signal hybrid –pi Model of SiGe HBT is

$$r_{be} = \frac{V_T}{I_B} \quad \text{.....(2.47)}$$

Base current(from eqn 2.9)

The Y-Parameters of the Intrinsic small signal of SiGe HBT hybrid-pi model (Fig2.7) is

$$Y_{11} = \frac{I_1}{V_1} \quad \text{.....(2.48)}$$

$$Y_{12} = \frac{I_1}{V_2} \quad \text{.....(2.49)}$$

$$Y_{21} = \frac{I_2}{V_1} \quad \text{.....(2.50)}$$

$$Y_{22} = \frac{I_2}{V_2} \quad \text{.....(2.51)}$$

2.3.5 S-Parameters of Intrinsic HBT:

S-parameters have almost similar information like Z-, Y-, or H-parameters. But the difference between them is that the dependent and independent variables are no longer simple voltages and the currents in S-parameters. In addition, in the s-parameter four “voltage waves” are produced by linear combinations of the simple variables. These voltage

waves hold the identical information because they are chosen to be linearly independent. Transmission line techniques are used to compute s-parameters at high frequencies by properly selection of these combinations [31].

S-parameters are mostly used for networks operating at radiofrequency (RF) and Microwave Frequencies where signal power and energy considerations are more easily quantified than currents and voltages. S-parameters change with the measurement frequency, so frequency must be specified for any S-parameter measurements stated, in addition to the characteristic impedance or system impedance.

S-parameters are important in microwave design because they are easier to measure and to work with at high frequencies than other kinds of two port parameters.

S-parameters have been used extensively in the analysis of Microwave Device. S-parameters of a SiGe HBT will thoroughly depend on the size of transistor, frequency of operation as well as on biasing condition.

S11 and S22 are conveniently displayed on a Smith chart,

S21 and S12 are typically displayed on a polar plot

S-parameters of the intrinsic small-signal model can be computed from the modeled Y-parameters of CE configuration.

Finally the Y-parameters of Intrinsic Small Signal SiGe HBT's are (2.48-2.51) converted to S-parameters of with 50Ω matched impedance.

2.3.6 Device Parameters:

- Ge mole fraction= 0.21
- Emitter doping = $3 \times 10^{20} \text{ cm}^{-3}$
- Base doping = $2 \times 10^{19} \text{ cm}^{-3}$
- Collector doping = $2 \times 10^{17} \text{ cm}^{-3}$
- Emitter width = 360×10^{-9}
- Base width = 40×10^{-9}
- Collector width = 1200×10^{-9}
- Area = $0.5 \times 2.5 \text{ } \mu\text{m}^2$
- $q = 1.6 \times 10^{-19} \text{ C}$
- $\epsilon_0 = 8.854 \times 10^{-14} \text{ F/cm}$
- Conduction band density $N_c = 2.8 \times 10^{19}$
- Valence band density $N_v = 1.04 \times 10^{19}$
- mobility of holes $\mu_p (\text{Si}) = 450 \text{ cm}^2/\text{V-S}$
- mobility of electrons $\mu_n (\text{SiGe}) = 2100 \text{ cm}^2/\text{V-S}$
- Dielectric Constant of Si = 11.9
- Dielectric of SiGe = 12.77 (from eq 2.3)
- Lattice constant of Si = 5.4310
- Lattice constant of SiGe = 5.4785 (from eq 1)

2.3.7 Simulation Results:

The hybrid, or H- parameters are used for transistors h_{21} is good representation of the current gain β for a typical microwave common-emitter transistor. The frequency where $|h_{21}| = 1$ for common emitter transistor is the f_T of the transistor. For a Base constant doping of Intrinsic small signal SiGe HBT cutoff frequency f_T is 45-GHz(2.10).

The cutoff frequency of Intrinsic Small signal Graded-base SiGe HBT is 65-GHz. the base transit time in a heterojunction bipolar transistor (HBT) can be shortened by providing a quasi-field across the base, i.e., grading the bandgap (Ge concentration) across the base. so higher Cut-off Frequency f_T in intrinsic Small signal Graded-base SiGe HBT(Fig2.11).

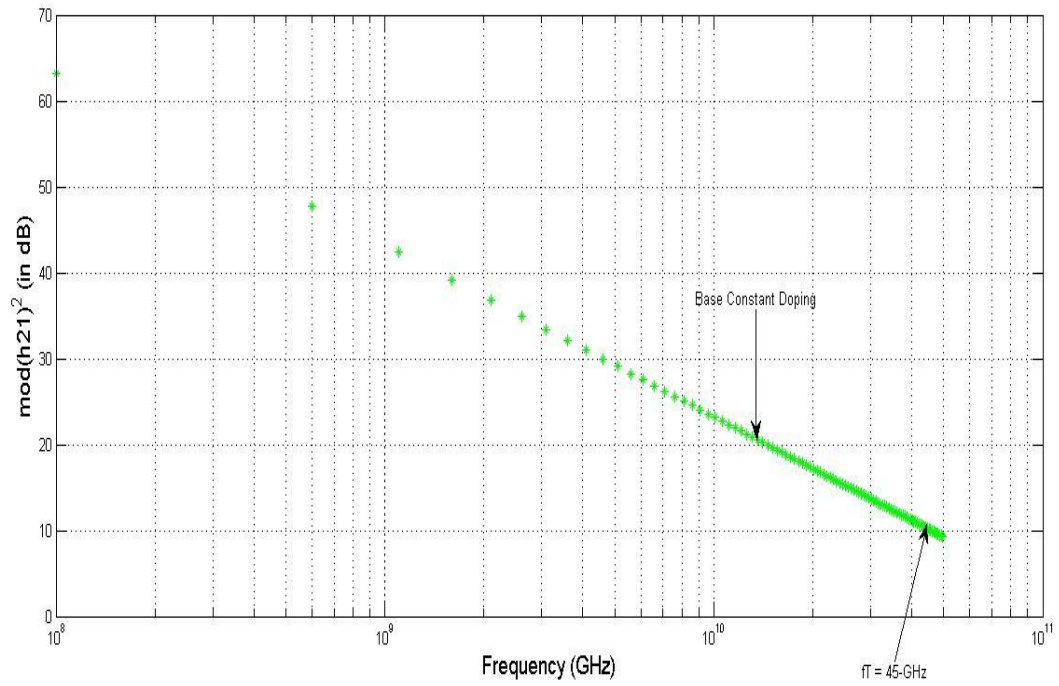


Figure 2.10 $|h_{21}|$ versus frequency of Intrinsic Small signal of uniform-Base SiGe HBT

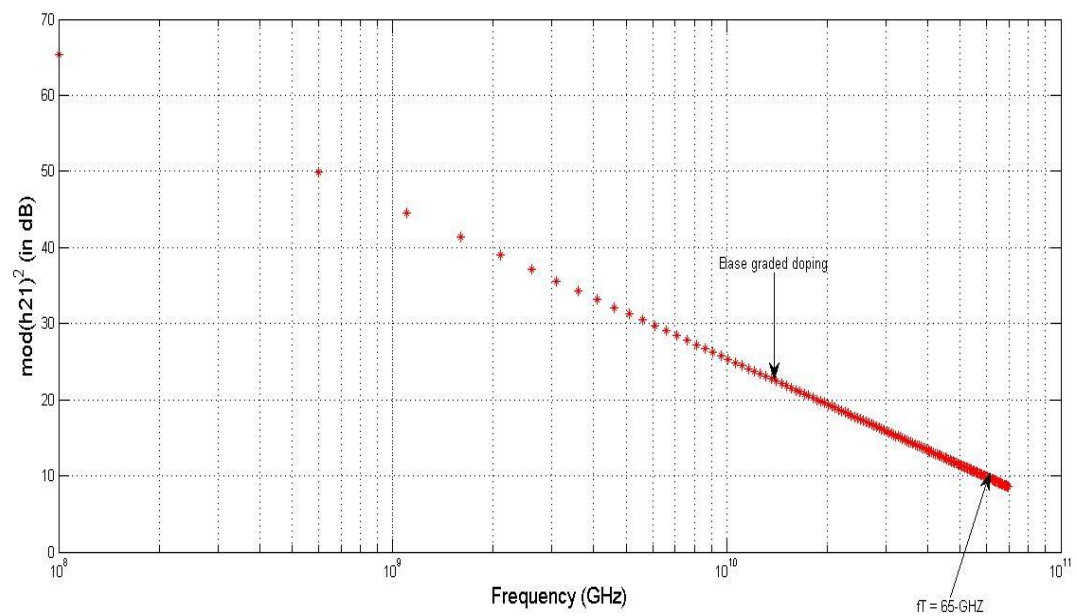


Figure 2.11 $|h_{21}|$ versus frequency of Intrinsic Small signal of Graded-Base SiGe HBT

Linearly Graded-Base SiGe HBT having higher cutoff frequency than Uniform– Base SiGe HBT. Because the base transit time in a heterojunction bipolar transistor (HBT) can be reduced by providing a quasi-field across the base, i.e., grading the bandgap (Ge concentration) across the base. so higher Cut-off Frequency f_T in intrinsic Small signal Graded-base SiGe HBT(Fig2.12).

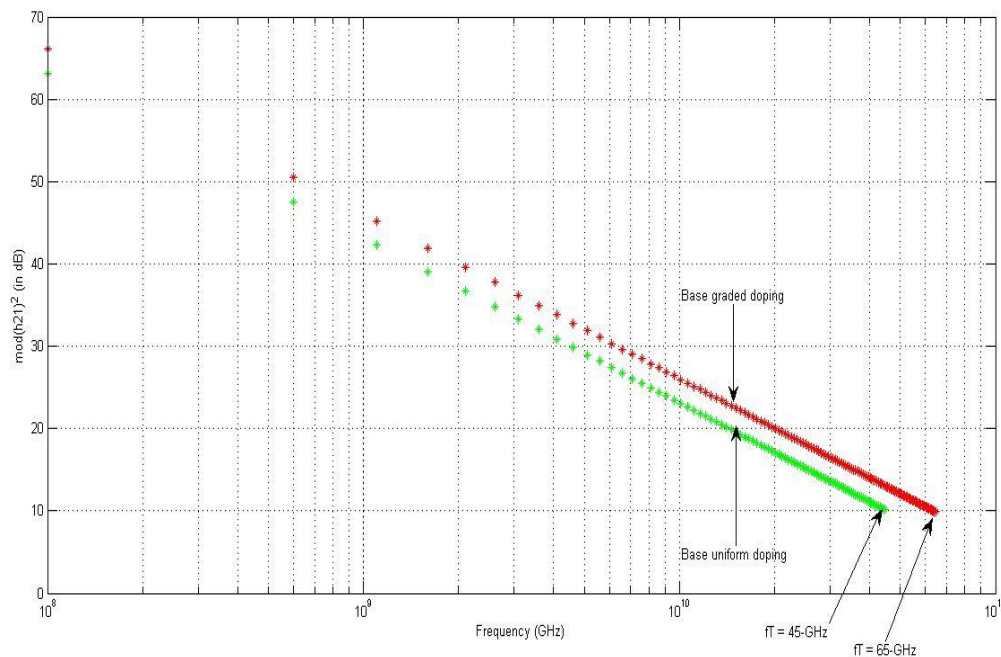


Figure 2.12 $|h_{21}|$ vs frequency of intrinsic Small Signal of Uniform Base and Graded-Base SiGe HBT

When the h_{21} is constant at low frequencies, and then decreases at high frequencies. Base width is decreasing from 40nm to 10nm h_{21} is increasing 45-GHz to 100GHz

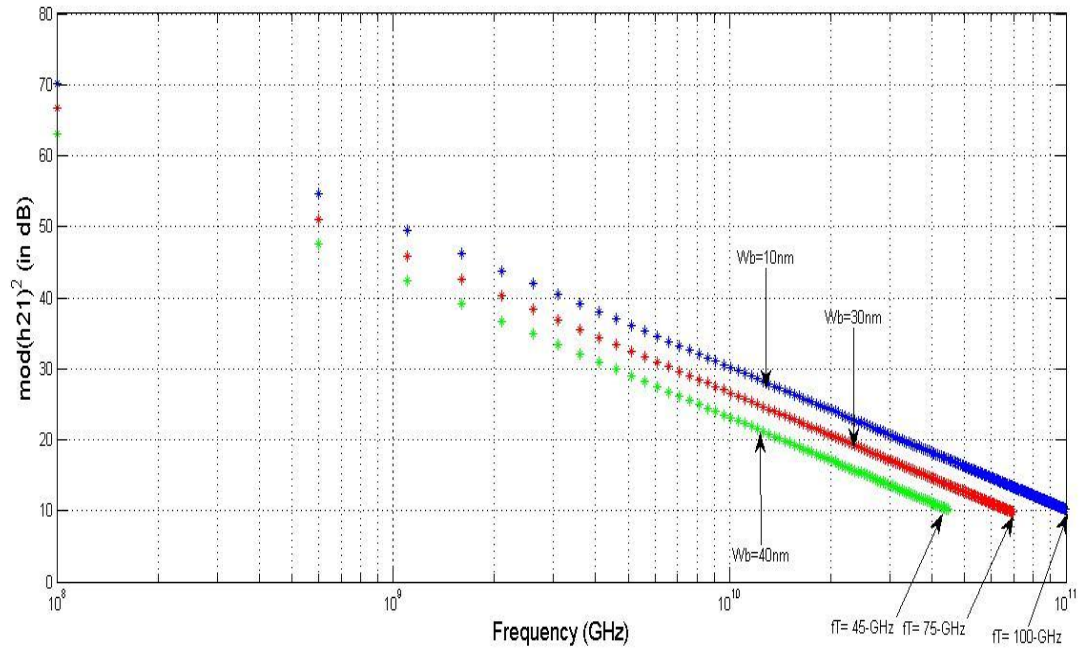


Figure 2.13 $|h_{21}|$ vs frequency of intrinsic Small Signal SiGe HBT for various bandwidths

S_{12} :

S_{12} is clock-wise with increasing frequency.

While $S_{12} = 0$ at low frequencies its curves tend towards $S_{12} > 0$ for high frequencies.

S_{12} shows a smaller +ve reactance because of the higher BC depletion Capacitance.

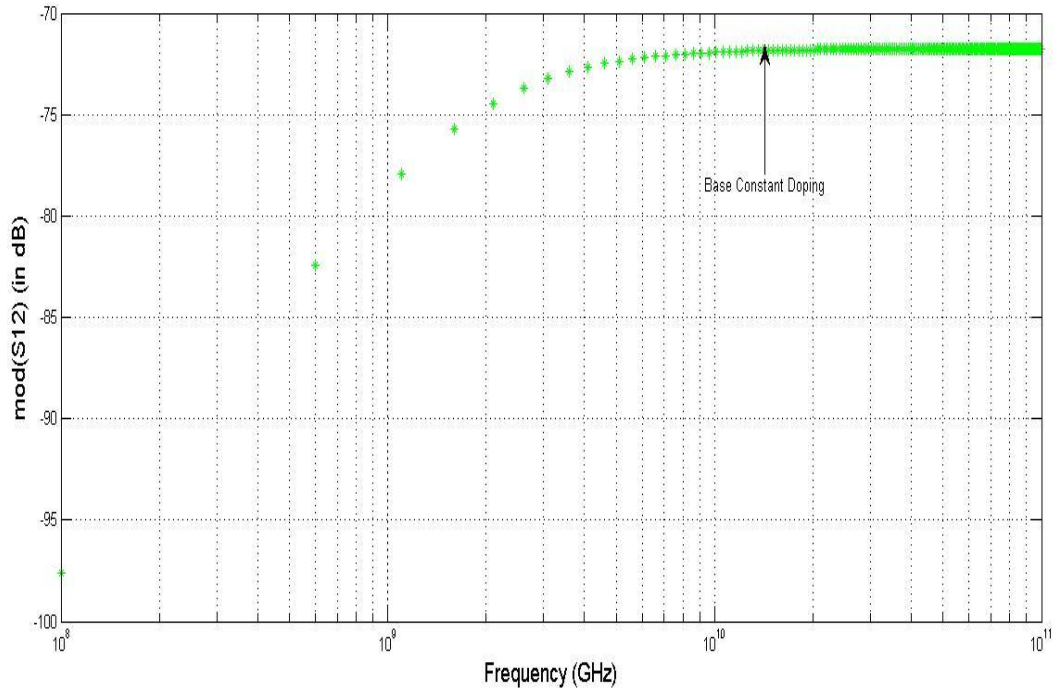


Figure 2.14 S_{12} vs Frequency of base constant doping Intrinsic HBT

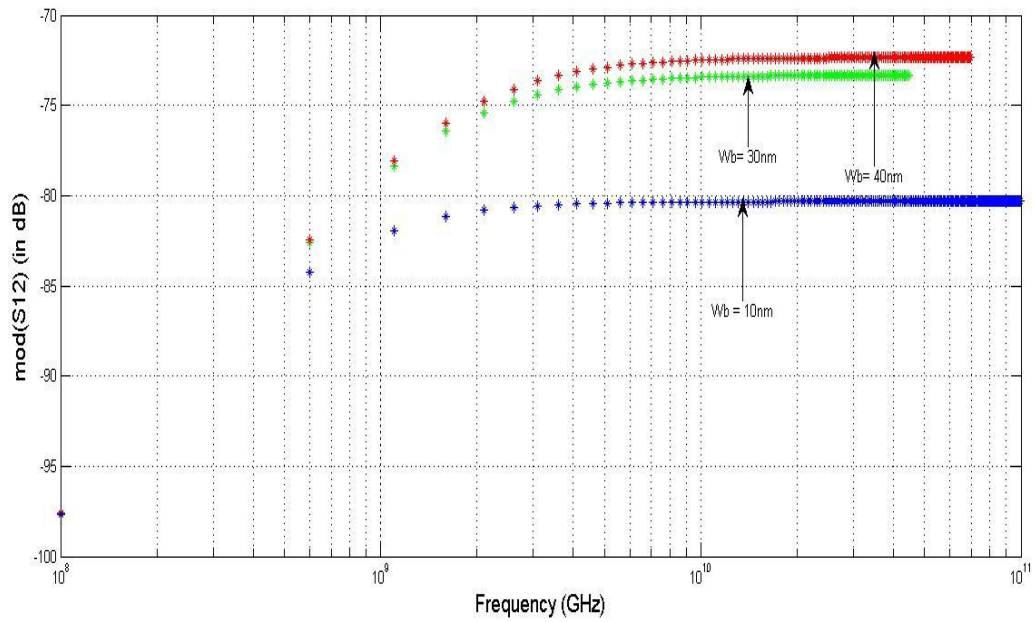


Figure 2.15 S_{12} vs Frequency of of intrinsic Small Signal SiGe HBT for various bandwidths

S_{21} :

The S_{21} magnitude decreases with increasing frequency, as expected, because of decreasing forward transducer gain, while S_{21} is larger at higher I_C because of the higher f_T at that bias current. The transconductance (gm) contains a time delay component (τ) which changes the phase of S_{21} -parameter at high-frequencies [19].

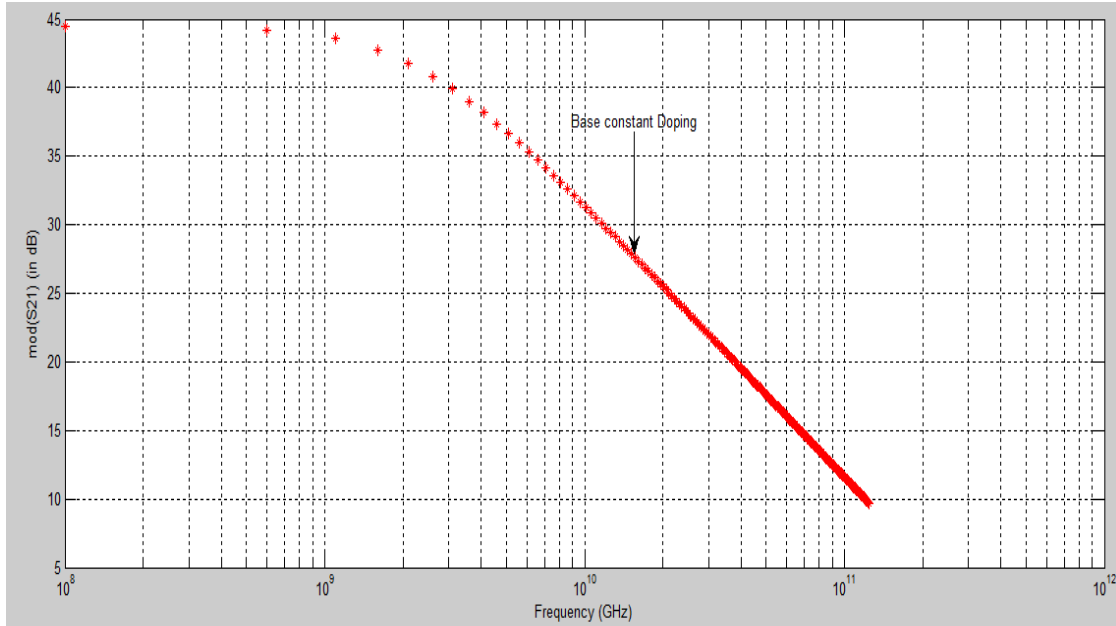


Figure 2.16 S_{21} vs Frequency of base constant doping Intrinsic HBT

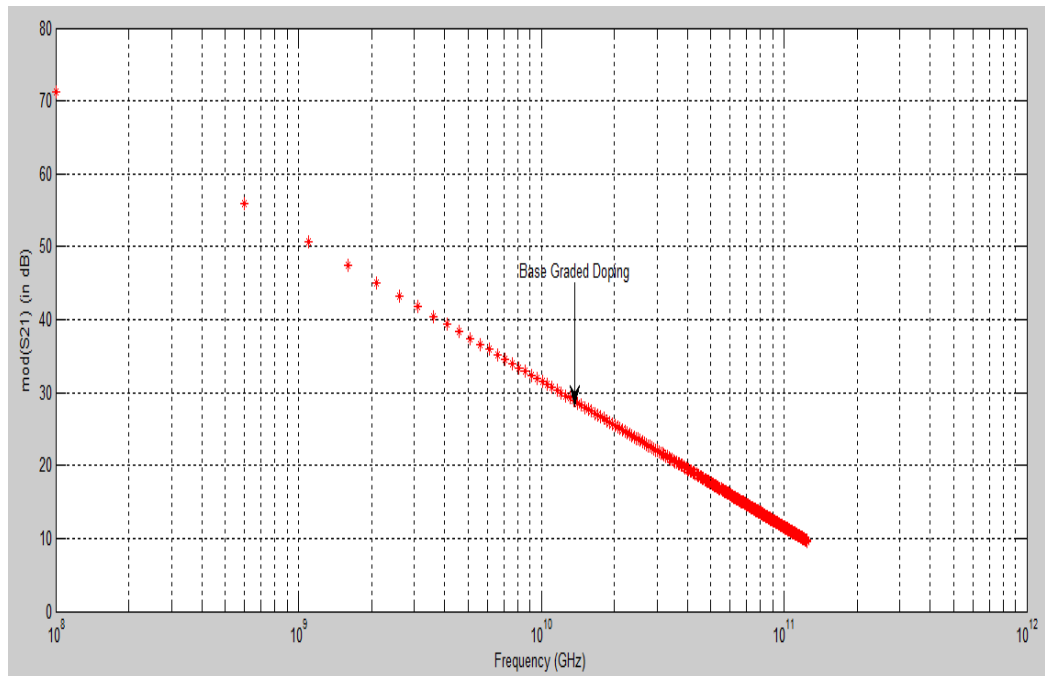


Figure 2.17 S_{21} vs Frequency of Intrinsic small signal Graded-base SiGe HBT

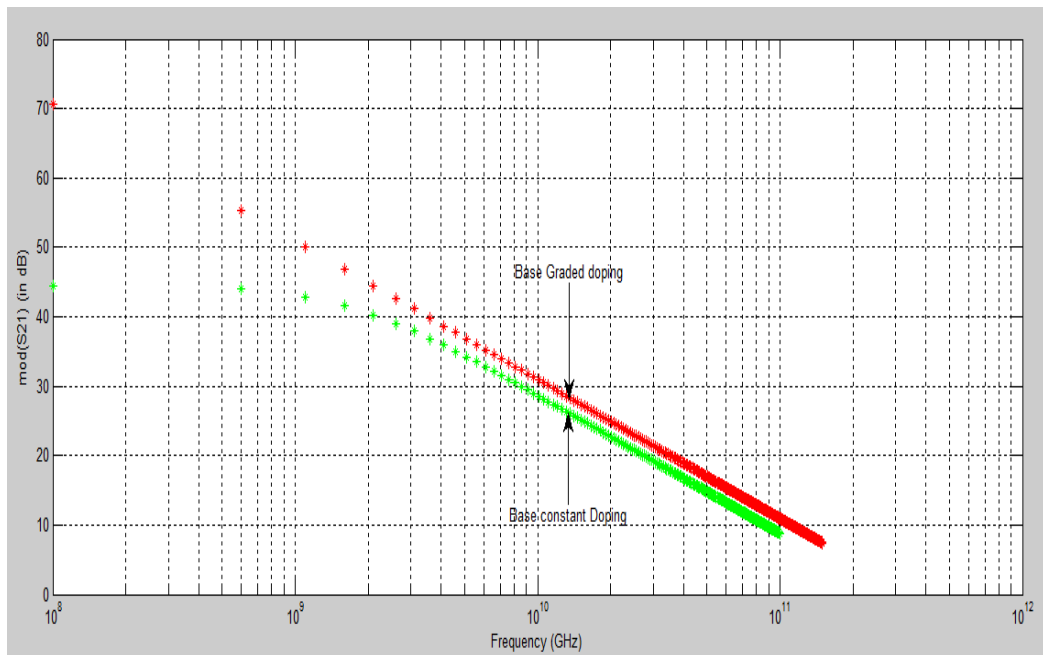


Figure 2. 18 S_{21} vs Frequency of Intrinsic small signal base constant and Graded-base SiGe HBT

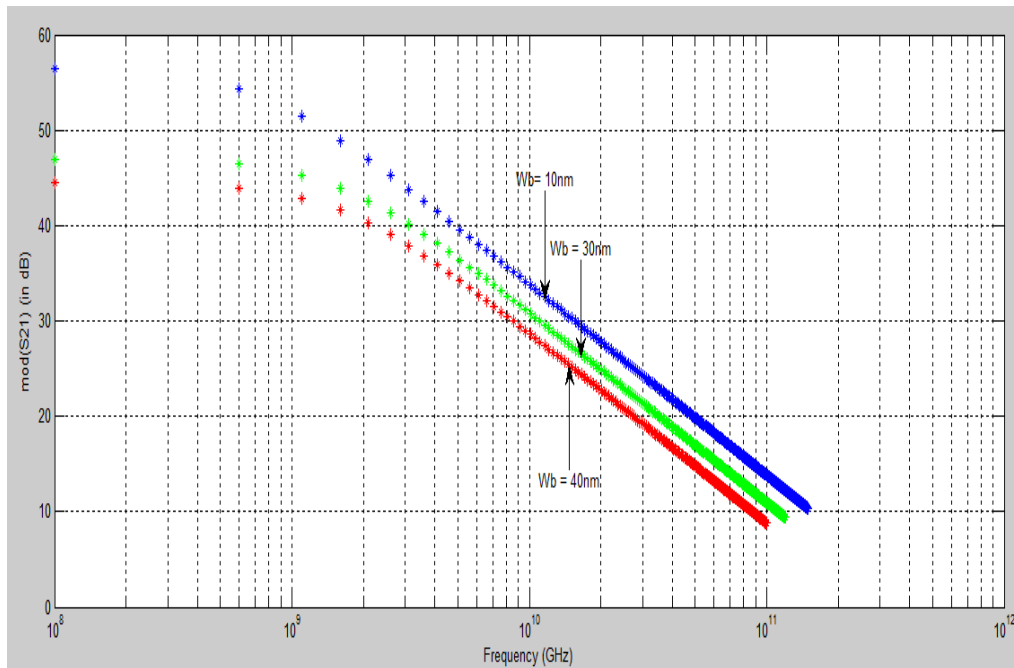


Figure 2. 19 S_{21} vs Frequency of Intrinsic small signal model SiGe HBT various basewidths.

2.4 Extrinsic Small signal SiGe HBT:

Extrinsic Small Signal SiGe HBT of Hybrid- π equivalent model is the bias independent of extrinsic elements. Extrinsic elements are Fixed base, collector and emitter resistances and substrate parasitic capacitances (C_{bcp} , C_{cso}) and substrate resistance (R_s). In SiGe HBT devices a large part of the total capacitance between base-emitter and base-collector terminals is due to fixed oxide capacitances shown in Fig as (C_{beo}).

The small-signal equivalent circuit model seen in Fig2.6 should be able to accurately describe the behavior for a SiGe HBT from DC to frequencies in excess of the f_T for the devices [10].

Extrinsic Base Resistance ():

The Extrinsic base resistance is the resistance between the edge of the active transistor area and the base contact shown in fig, and it is dependent on the transistor geometry and extrinsic base sheet resistance.

$$\frac{R_{be}}{R_{sh}} = \frac{L}{W} \quad \dots\dots\dots (2.52)$$

Number of base contacts ,

= contact resistance ,

width of base ,

length of base ,

Extrinsic base sheet resistance, Ω/\square

= -

ρ = resistivity,

t= thickness of base

S-parameters of the complete small signal model of HBT is computed by using Y-parameters using equations from(2.48 to 2.51).

- 1) The Y-parameters of the intrinsic model , as in eqs.(3.1) to 3.4 are added to the Y-parameters of C_{bep} .

.....(2.53)

- 2) The Resultant Y-parameters are converted to Z-parameters and added to the emitter resistance.

= +(2.54)

- 3) The Resultant Z-parameters are converted ABCD-parameters and multiplied with the ABCD-parameters of base and collector networks.

=

$$\frac{1}{Y_{bco}} = \frac{1}{Y_{bco}} + \frac{1}{Y_{bco}} \quad \text{..... (2.55)}$$

- 4) The resultant ABCD-parameters are converted to Y-parameters and added to Y-parameters of C_{bco} .

$$\text{..... (2.56)}$$

- 5) Finally, the Y-parameters are converted to S-parameters with 50-Ω matched load.

2.4.1 Simulation Results:

S-parameters of complete small signal model of SiGe HBT calculated by using model equations for small signal model of intrinsic HBT within the frequency range of 0.2-50GHz using parasitic effect(fig2.21).

Polar Plot:

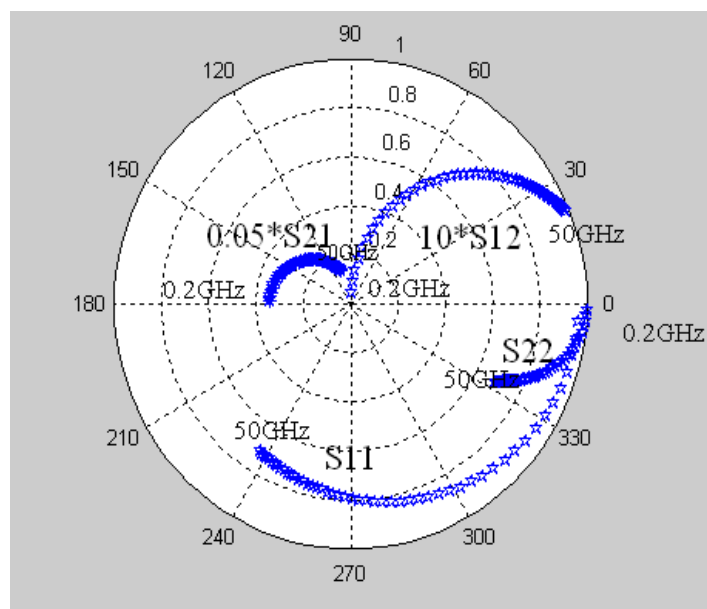


Figure 2. 20 : S-parameters are calculated in the frequency range of 0.2-50GHz with parasitic effects

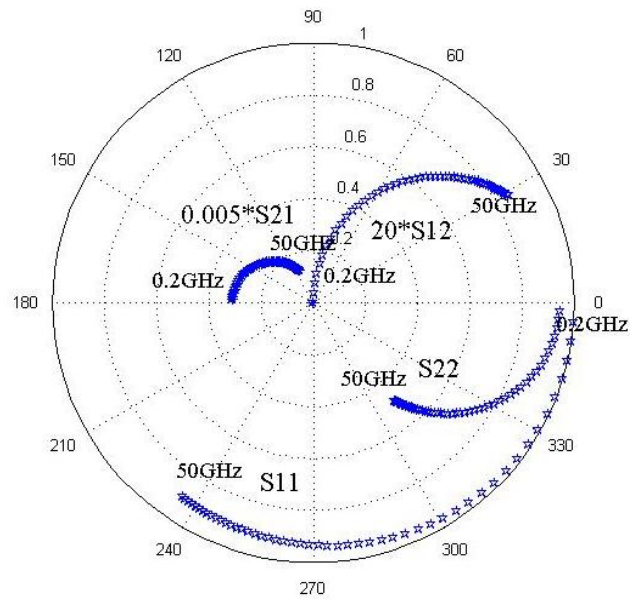


Figure 2. 21 S-parameters are calculated by using model equations in the frequency range of 0.2-50Ghz with parasitic effects

Smith Chart:

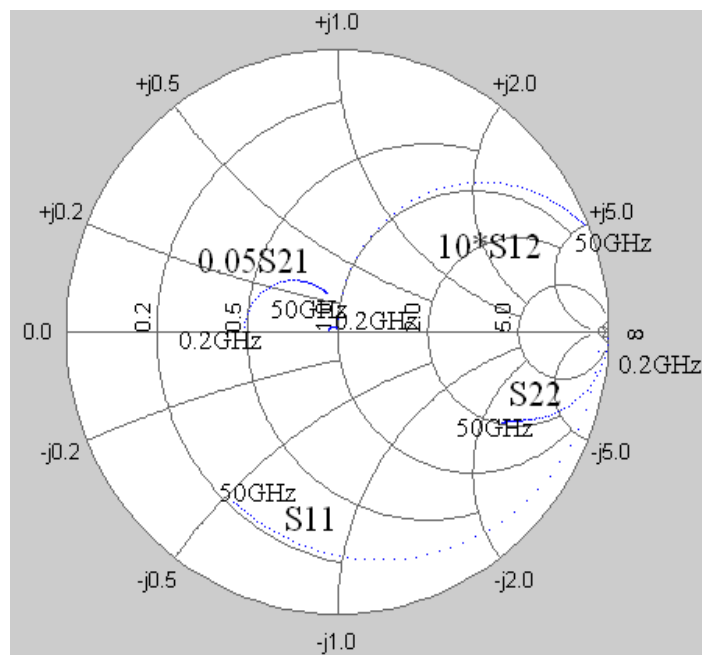


Figure 2. 22 S-parameters are calculated in the frequency range of 0.2-50GHz with parasitic effects

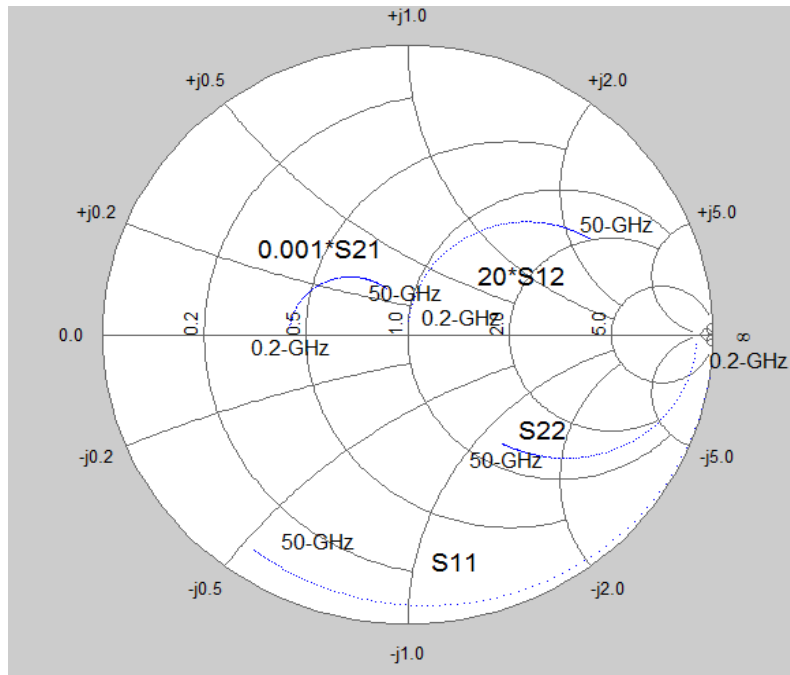


Figure 2. 23 : S-parameters are calculated by using model equations in the frequency range of 0.2-50GHz with parasitic effects

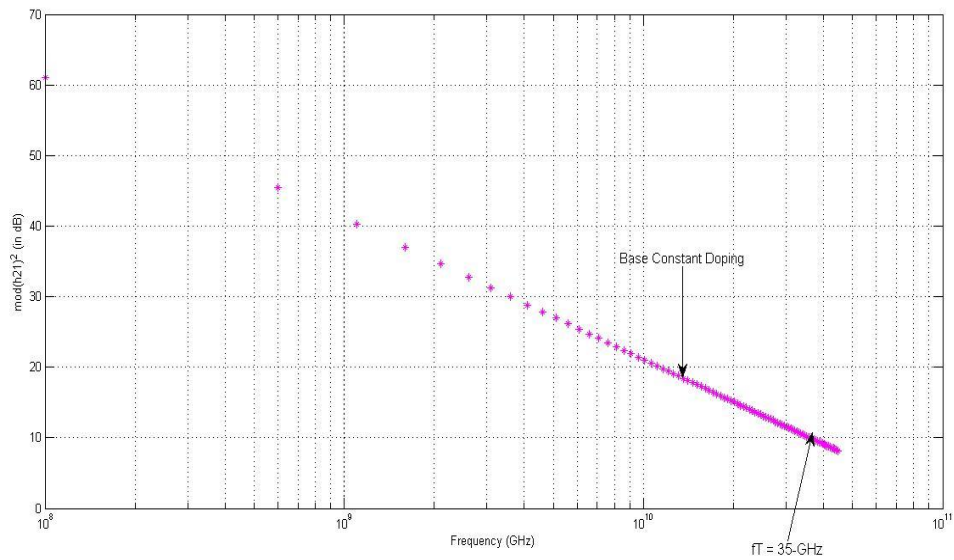


Figure 2. 24 $|h_{21}|$ vs frequency of complete Small Signal of Uniform Base SiGe HBT

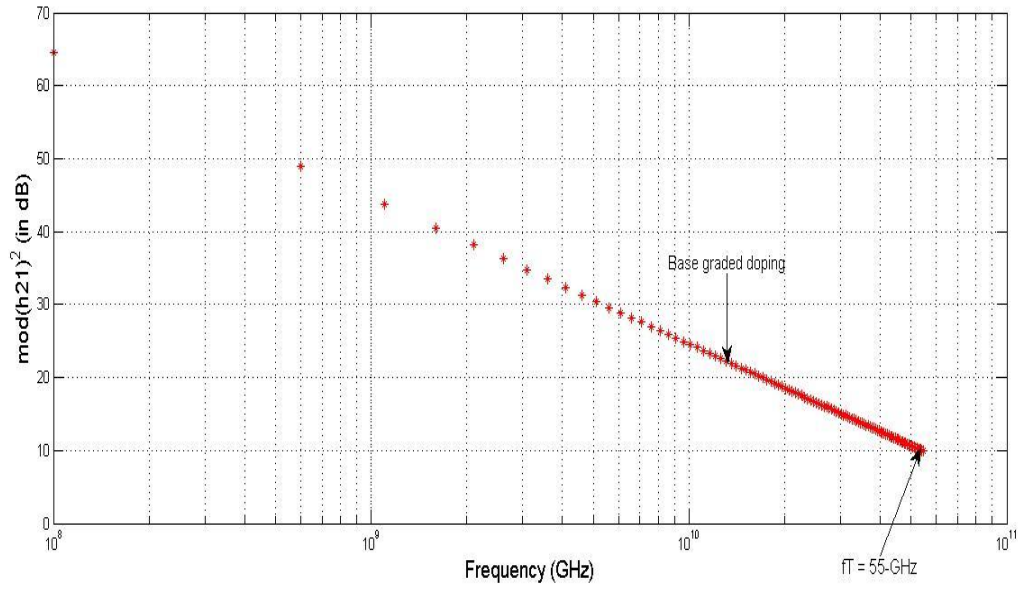


Figure 2. 25 $|h_{21}|$ vs frequency of complete Small Signal of Graded-Base SiGe HBT at $f_T = 55$ -GHz

Linearly Graded-Base Small Signal Model of SiGe HBT is providing a built in electric field in the base which accelerates the carrier across the base, reducing the base transit time. so higher Cut-off Frequency f_T in Small signal hybrid-pi model of Graded-base SiGe HBT than Uniform-Base SiGe HBT(Fig2.24).

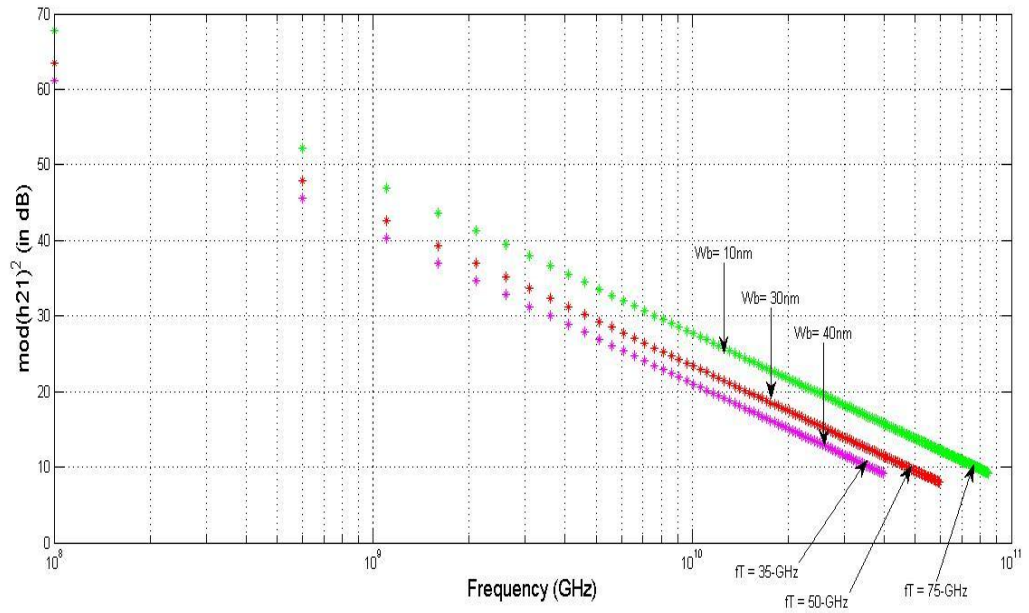


Figure 2. 26 $|h_{21}|$ vs frequency of complete Small Signal SiGe HBT of various base widths

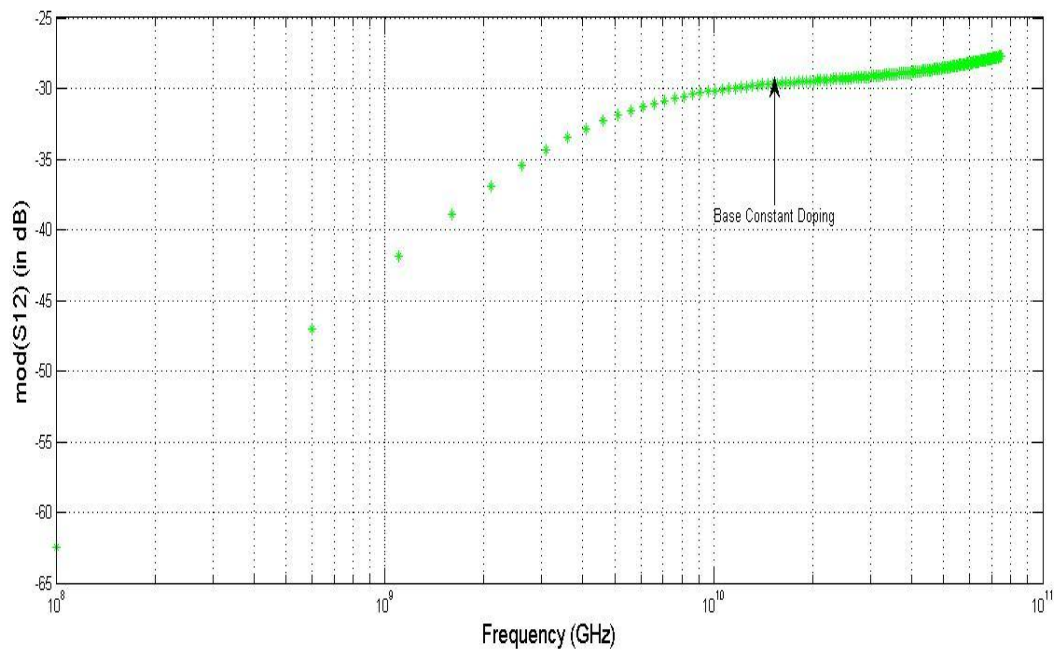


Figure 2. 27 S_{12} vs Frequency of complete small signal model of Uniform Base SiGe HBT

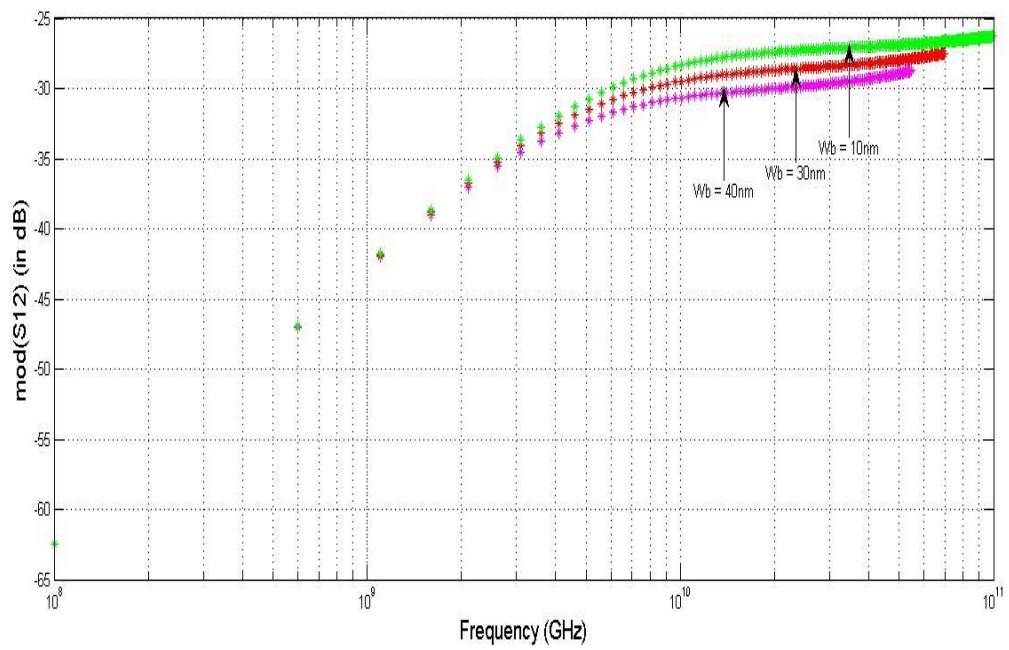


Figure 2. 28 S_{12} vs Frequency of complete small signal model SiGe HBT various basewidths

S_{21} :

The transconductance (g_m) contains a time delay component (τ) which changes the phase of S_{21} -parameter at high-frequencies. The S_{21} magnitude decreases with increasing frequency, as expected, because of decreasing forward transducer gain, while S_{21} is larger at higher I_C because of the higher f_T at that bias current [19].

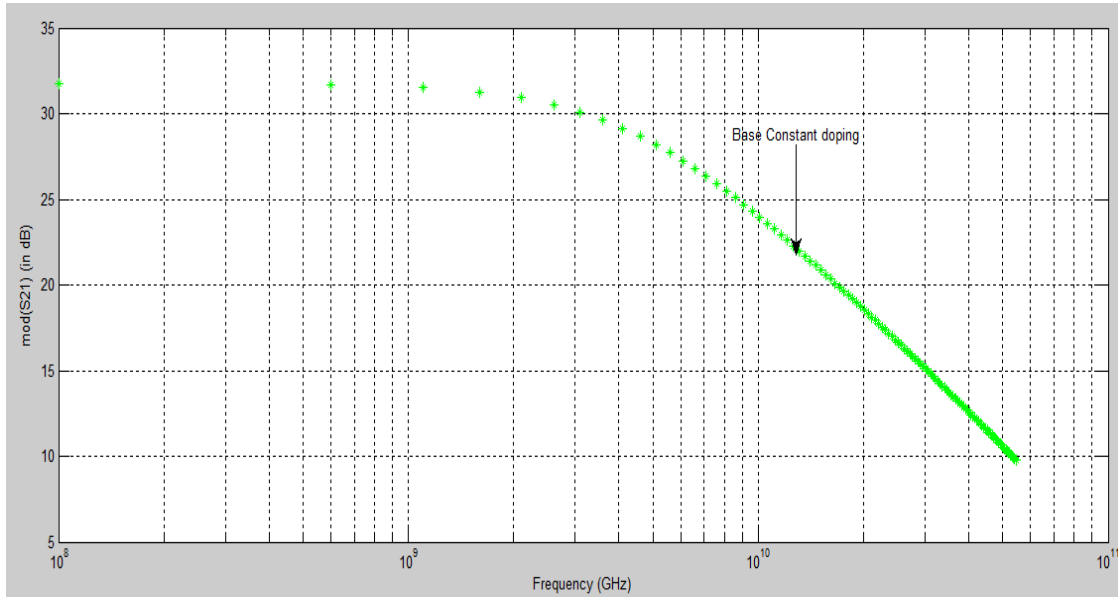


Figure 2.29 S_{21} vs Frequency of complete small signal model of Uniform Base SiGe HBT

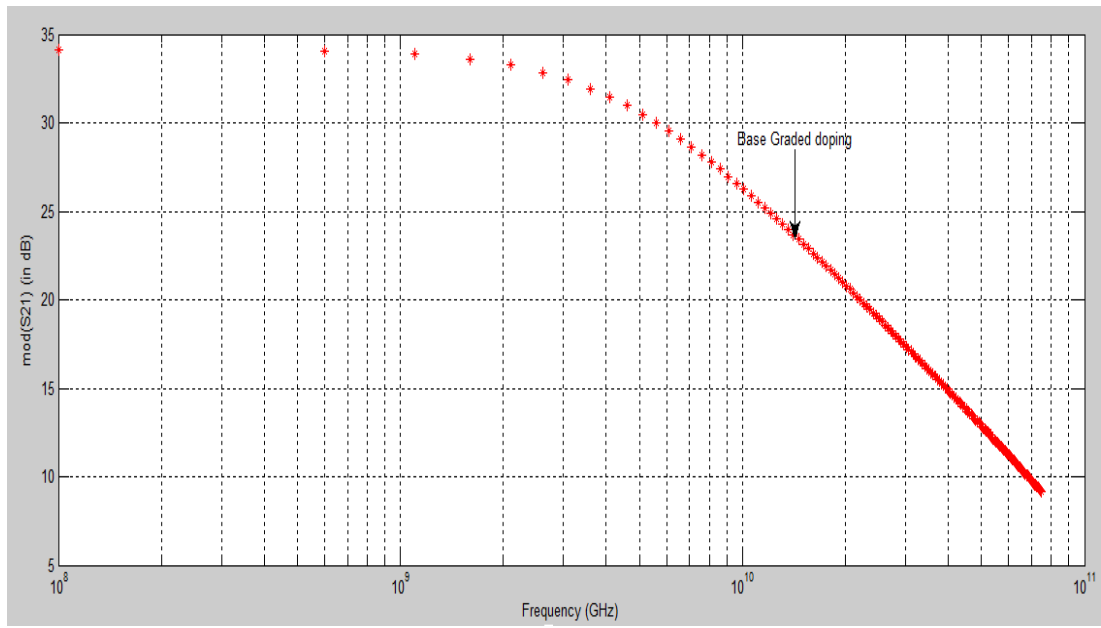


Figure 2.30 S_{21} vs Frequency of complete small signal model of Grded-Base SiGe HBT

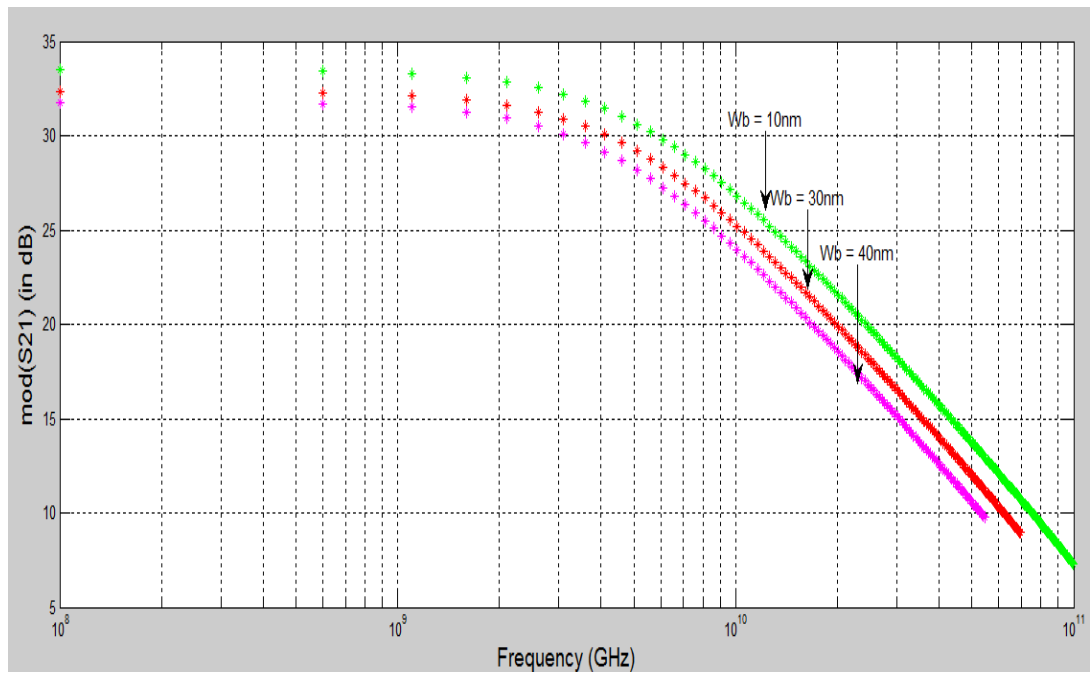


Figure 2.31 S_{21} vs Frequency of complete small signal model SiGe HBT various base widths

2.5 Comparison of intrinsic and extrinsic SiGe HBT

Intrinsic Small Signal model of SiGe HBT having higher Frequency than Complete Small Signal Model of SiGe HBT because Complete Small Signal model of SiGe HBT including a substrate parasitic effects because parasitic capacitance and resistances are effects at high frequency .

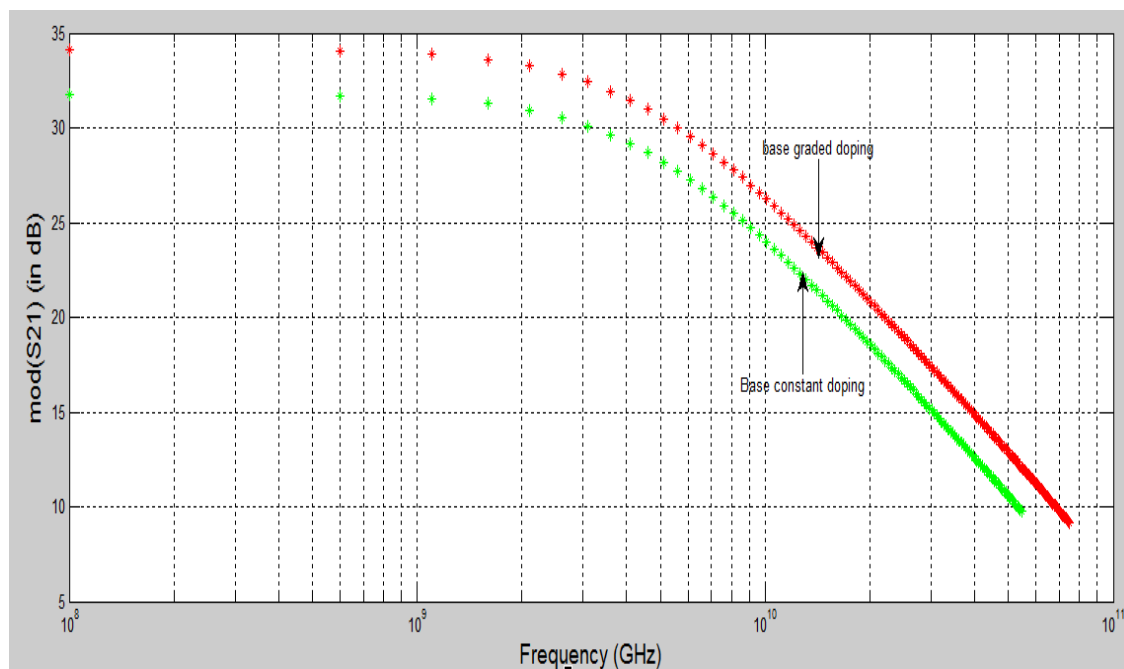


Figure 2.32 S_{21} vs Frequency of Intrinsic and Extrinsic Small SiGe HBT

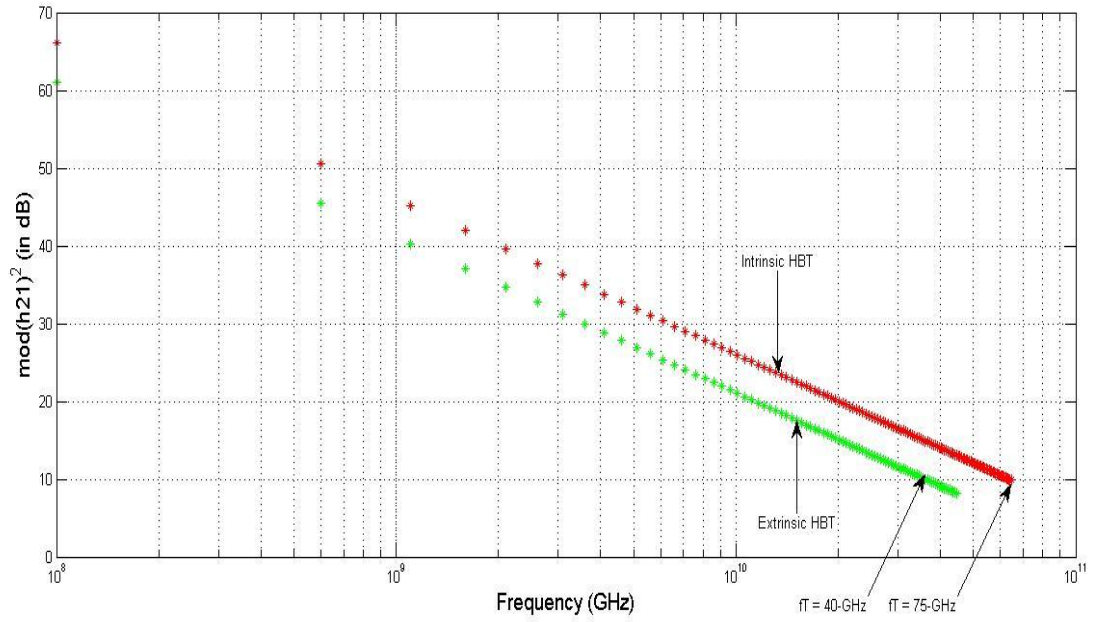


Figure 2.33 h_{21} vs Frequency of Intrinsic and Extrinsic SiGe HBT

2.6 SiGe HBT for Different Ge Concentrations

The cut-off frequency (f_T) of the HBT increases with the increase in the Ge-content, it increases with the change in profile gradually from ‘uniform –base doping ’ to ‘Graded-base doping.

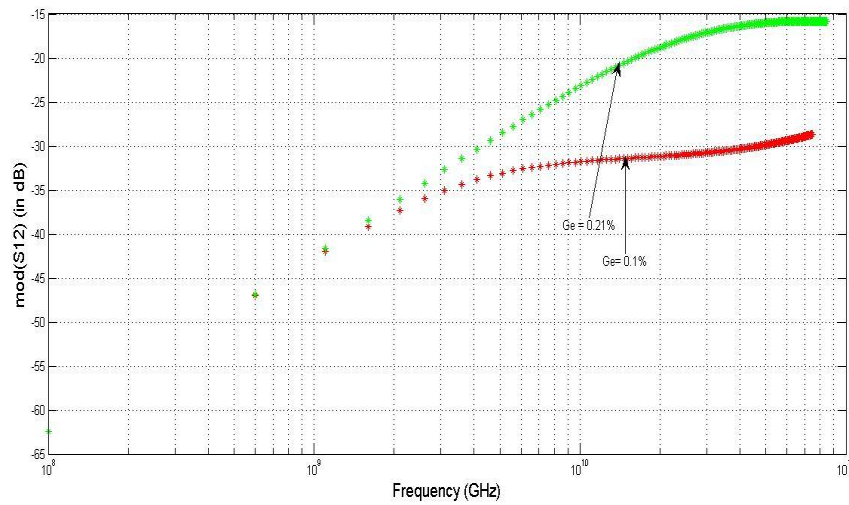


Figure 2. 34 S_{12} vs Frequency of complete Small Signal SiGe HBT for Different Ge concentrations

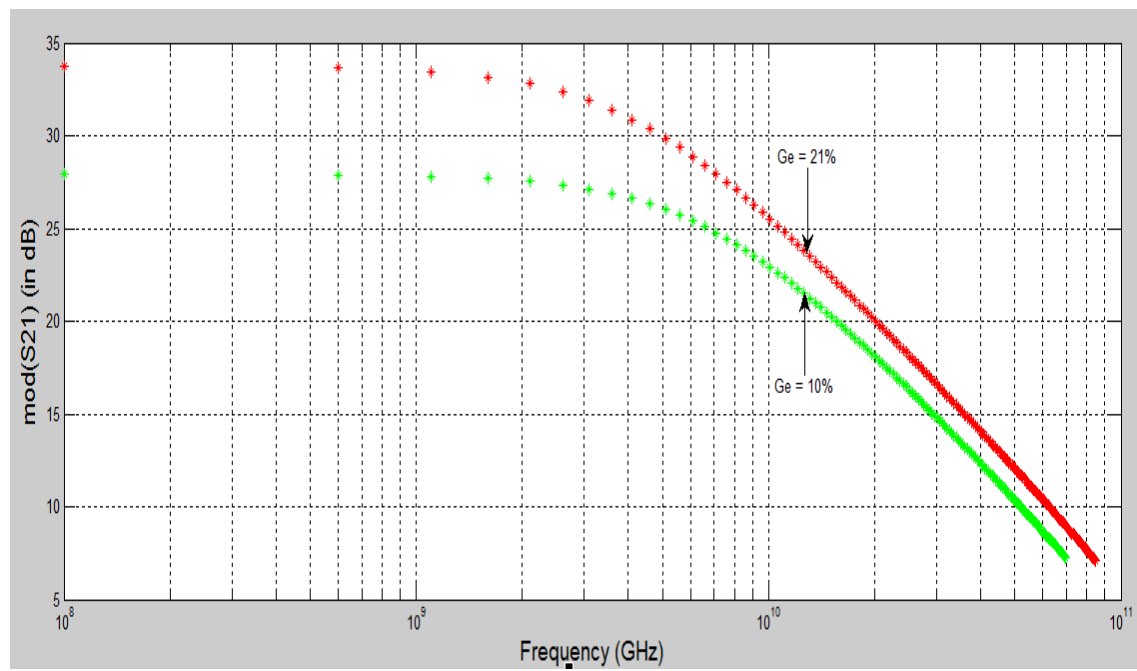


Figure 2.35 S_{21} vs Frequency of complete Small Signal SiGe HBT for Different Ge concentrations

CHAPTER 3

CONCLUSION

3.1 Conclusion:

In this thesis, we studied the material properties of the SiGe HBT. Studied the characteristics of the Uniform-Base and graded- Base SiGe HBT. Graded-Base SiGe HBT having higher current gain than Uniform Base doping because the germanium content is graded across the base region of the transistor, inducing an electric field of the device. This field accelerates injected minority electrons as they traverse the base. S-parameters of complete Small Signal hybrid- π model of SiGe HBT calculated by using model equations of small signal model of intrinsic HBT within the frequency range of 0.2-50-GHz using parasitic effects. Compares the S-parameters of Complete Small Signal model of SiGe HBT's and Intrinsic Small Signal Model of SiGe HBT's for Both Uniform-Base doping and Graded-base Doping. In Complete Small Signal SiGe HBT Graded-base Doping have higher frequency than Uniform-Base Doping. Intrinsic Small Signal model of SiGe HBT having higher Frequency than Complete Small Signal Model of SiGe HBT because Complete Small Signal model of SiGe HBT having parasitic effects.

S-parameters of complete Small Signal hybrid- π model of SiGe HBT calculated by using model equations of small signal model of intrinsic HBT for different Ge concentrations of Ge 10% and 21%. The cut-off frequency () of the HBT increases with the increase in the Ge-content, it increases with the change in profile gradually from 'uniform –base doping' to 'Graded-base doping'.

3.2 Scope for Future Work

This thesis can be further developed in the areas like Power gain, Stability, MSG (Maximum Stable Gain), MAG(Maximum Available Gain), and Phase measurements for different Ge Concentrations / profiles.

References :

- [1]. H. Kroemer, "Theory of a wide- gap emitter for transistors " *Proc. IRE*, vol. 45, no. 11, pp. 1535-1537, Nov. 1957
- [2]. H. Kroemer, "Heterostructure bipolar transistors and integrated circuits," *Proc. IEEE*, vol. 70, no. 1, p. 13, 1982.
- [3] J. W. Matthews and A. E. Blakeslee, "Defects in epitaxial multilayers -I: Misfit Dislocations in layers," *J. Crystal Growth*, vol. 27, pp. 118–125, 1974.
- [4] J.W. Matthews and A. E. Blakeslee "Defects in epitaxial multilayers—II: Dislocation pile-ups, threading dislocations, slip lines and cracks," *J. Crystal Growth*, vol.32, pp. 265–273, 1975.
- [5] SS Iyer, GL Patton, JMC Stork "Heterojunction Bipolar Transistors Using SiGe Alloys" *IEEE Transactions On Electron Devices*, vol.36, no. 10, October 1989.
- [6] Maurizio Arienzo, James H. Comfort, Emmanuel F. Crabbe, David L. Harame, Subramanian S. Iyer, Bernard S. Meyerson, Gary L. Patton, Johannes M.C. Stork and Yuan-Chen Sun "SiGe HETEROJUNCTION BIPOLAR TRANSISTORS" *Materials. Research. Society. Symp. Proc.* Vol. 220. 1991
- [7] J. S. Yuan , "Modeling of Si/Si_{1-x}Ge_x Hetrojunction Bipolar Transistors" *Solid-State Electronics* , vol. 35, no.7 , pp 921-926, 1992
- [8] E. Kasper, A. Gruhle and H. Kibbel "High Speed SiGe-HBT With Very Low Base Sheet Resistivity" in *Tech. Dig. Int. Electron Device Meeting*, pp. 79–81,1993.
- [9] Douglas A. Teeter, Member, , Jack R. East, Richard K. Mains, and George I. Haddad, "Large-Signal Numerical and Analytical HBT Models" *IEEE transactions on electron devices* ,vol. 40, no.5 , may 1993
- [10] J. D. Cressler, D. L. Harame, J. H. Comfort, J. M. C. Stork, B. S. Meyerson, and T. Tice, "Silicon-germanium heterojunction bipolar technology: The Next leap in silicon? *Tech. Dig. IEEE Int. Solid-State Circuits Conf.*, pp. 24–27, 1994.
- [11] J. D. Cressler, "Re-engineering silicon: Si-Ge heterojunction bipolar technology," *IEEE Spectrum Mag.*, pp. 49–55, Mar. 1995.
- [12] J.D. Cressler. SiGe HBT technology: "a new contender for Si-based RF and Microwave circuit applications". *IEEE Trans. Microw. Theory Tech.*, vol. 46, issue 5, 572 (1998).
- [13] Timothy K. Cams, , Sang K. Chun, Martin Tanner, Kang L. Wang, Ted I. Kamins, , John E. Turner, Donald Y. C. Lie, Marc-A. Nicolet, and Robert G. Wilson "Hole

- Mobility Measurements in Heavily Doped $\text{Si}_{1-x}\text{Ge}_x$ Strained Layers” *IEEE Transactions on electron devices*, vol. 41, no. 7, July. 1994
- [14] Slavko Amon “Modeling Base transport properties of npn SiGe HBT” *IEEE Transactions* 1996
- [15] S.T. Chang , C.W. Liu , S.C. Lu “ Base transit time of graded-base Si/SiGe HBTs Considering recombination lifetime and velocity saturation”, *Solid-State Electronics* vol. 48 , pp. 207–215, 2004.
- [16] Sami Bousnina, Pierre Mandeville, Ammar B. Kouki, , Robert Surridge, and Fadhel M. Ghannouchi, “Direct Parameter-Extraction Method for HBT Small-Signal Model” *IEEE transactions on Microwave Theory And Techniques*, vol. 50, no. 2, Feb. 2002
- [17] Kyungho Lee, Kwangsik Choi, Sang-Ho Kook, Dae-Hyung Cho, Kang-Wook Park, And Bumman Kim, “Direct parameter Extraction of SiGe HBTs for the VBIC Bipolar compact model” *IEEE Transaction on electronic Devices*, vol. 52, No. 3, March, 2005
- [18] Mukul K. Das, N. R. Das, and P. K. Basu “Effect of Ge content and profile in the SiGe Base on the performance of a SiGe/Si Heterojunction Bipolar Transistor” *Inc. Microwave Opt Techno Lett.* 47, pp. 247–254, 2005
- [19] Rached Hajji and Fadhel M. Ghannouchi “Small-Signal Distributed Model for GaAs HBT’s and S-Parameter Prediction at Millimeter-Wave Frequencies” *IEEE Transaction Electron devices*, Vol. 44, NO. 5, MAY 1997
- [20] Shinichi Tanaka,, Yasuchi Amamiya, Seiichi Murakami, Norio Goto, Yoichiro Takayama and Kajuhika Honjo “ Design Considerations for Millimeter-Wave Power HBT’s Based on Gain Performance Analysis” *IEEE Transaction on electronic Devices*, vol.45 , no.1, January 1998
- [21] H.J.Osten, D.Knoll, B. Heinemann, H. Rucker, and B. Tillack “Carbon Doped SiGe Heterojunction Bipolar Transistors for High Frequency Applications” *IEEE Transaction on* 1999
- [22] Mukul K. Das, N. R. Das, P. K. Basu, “Performance Analysis of a SiGe/Si Heterojunction Transistor for Different Ge-composition” *Proc. Of the international Conf.*, 2005.
- [23] Guogong Wang, Jonghoo Park, Hui li, Zhenqiang Ma, Donald Lie, Jerry Lopez, and A. M. Hurtado “On The influences of device size on the small- and large-signal

- Performance of SiGe power HBTs” *IEEE Transactoins Electronic Devices on* 2006
- [24] Hai Huang,Zhenqiang Ma and Pingxi Ma and Marco Rananelli “Influence of Substrate Parasitic Effects on Power Gain Relation between CE and CB SiGe HBTs” *IEEE*, 2008.
 - [25] Pradeep Kumar and R. K. Chauhan, “Device Parameter Optimization of Silicon Germanium HBT for THz Applications”, *International Journal on Electrical Engineering and Informatics* – vol, 2, no. 4, 2010
 - [26] Peter Ashburn. “SiGe Hetrojunction Bipolar Transistors”, *Jhon Wiley & Sons Publication* (2003).
 - [27] John. D. Cressler , G.Niu “Silicon Germanium Heterojunction Bipolar Transistors”, 2003.
 - [28] J.W. Slotboom and H.C. de Graaff, ‘Measurement of bandgap narrowing in silicon bipolar transistors’, *Solid State Electronics*, 19, 857 (1976).
 - [29] J. Del Alamo, S. Swirhun and R.M. Swanson, ‘Measuring and modeling minority carrier transport in heavily doped silicon’, *Solid State Electronics*, 28, 47 (1985).
 - [30] R. Uscola and M. Tutt, “Direct extraction of equivalent circuit model parameters for HBTs” In *Proc. IEEE Int. Conf. Microelectronic Test Structures*, pp. 83–87. 2001,
 - [31] Stephen A. Maas “Nonlinear Microwave and RF Circuits”, *Artech House, Boston* 1997